

JOHNSON
GRANT
1N-37-OR
561653
508.

FINAL TECHNICAL REPORT

NASA GRANT NAG 9-311:

"THERMAL ANALYSES OF POWER SUBSYSTEM COMPONENTS"

Period of Performance:

May 1988 - December 1989

Principal Investigator:

**Jeffrey H. Morehouse
Mechanical Engineering Department
University of South Carolina
Columbia, South Carolina 29208**

NASA Technical Contact:

**Howard Wagner
Mail Stop EP5
NASA-Johnson Space Center
Houston, Texas 77058**

February 15, 1990

(NASA-CR-186314) THERMAL ANALYSES OF POWER
SUBSYSTEM COMPONENTS Final Technical Report,
May 1988 - Dec. 1989 (South Carolina Univ.)
50 p CSCL 13I

N90-29637

Unclas
63/37 0261653

TABLE OF CONTENTS

List of Figures.....	ii
INTRODUCTION.....	1
• OVERVIEW	
• BACKGROUND	
• OBJECTIVE	
Part 1: SELF REGULATING HEATER.....	2
• BACKGROUND THEORY	
• TEST RESULTS	
-Self-Limiting Equilibrium Test	
-Power versus Temperature Test	
-Electrical Resistivity Determination	
• CONCLUSIONS	
Part 2: FUEL CELL COOLANT SYSTEM.....	12
• FUEL CELL TESTS	
• PROBLEM AND APPROACH	
• THE MODEL	
• SIMULATION RESULTS	
-Steady-State 2-Stack Comparison	
-Transient 2-Stack Comparison	
-Purge Flow	
• CONCLUSIONS	
APPENDICES:	
A. NASA Fuel Cell Test Data.....	A-1
B. FCPSIM Computer Code Listing.....	B-1

LIST OF FIGURES

- Figure 1. Schematic of RAYCHEM Corporation self-limiting electrical resistance heater.
- Figure 2. The equations involved in the heating power illustrating the inverse relationship between resistance (temperature) and heating power.
- Figure 3. A schematic of the experimental test set-up. The BEMCO environmental chamber is located in BLDG. 352.
- Figure 4. Results of initial self-limiting equilibrium test with environmental chamber at 32° F (0° C).
- Figure 5. Heater power developed per foot of length as a function of heater temperature for the specific heater tested.
- Figure 6. Electrical resistivity relationship to material electrical resistance and heater geometry.
- Figure 7. Material resistivity as a function of its temperature.
- Figure 8. Schematic of the Orbiter fuel cell power plant with the coolant loop on the right-hand side.
- Figure 9. The FCPSIM interactive input format listing.
- Figure 10. Example listing of FCPSIM.OUT data listing for two times (5 minutes and 10 minutes).
- Figure 11. Comparison of results from steady state FCPSIM code to IFC code (manufacturer) for the 2-stack fuel cell power plant at low (2 kw) and high (12 kw) power.
- Figure 12. Comparison of transient temperatures from FCPSIM code and TTA test for 2-stack system at 4.1 kw with loss of external cooling sink.
- Figure 13. Comparison of transient temperatures from FCPSIM code and TTA test for 2-stack system at 3 kw with loss of external cooling sink.
- Figure 14. Comparison of transient temperatures from FCPSIM code and TTA test for 2-stack system at 2.5 kw with loss of external cooling sink.
- Figure 15. Comparison of transient stack-out temperatures for 3-stack system with and without purge during loss of external cooling sink at 4.1 kw (using FCPSIM code).

INTRODUCTION

OVERVIEW

This grant funded the development of the thermal characterization and analysis of two Space Shuttle power subsystem components: (1) a proposed APU line heater, and (2) the fuel cell coolant loop. The principal investigator was Dr. J.H. Morehouse who conducted the majority of the work on-site at Johnson Space Center (JSC) with the Power Branch (EP5) during July and August 1988.

BACKGROUND

The hiatus in the Space Shuttle (Orbiter) program provided time for an in-depth examination of all the subsystems and their past performance. Specifically, problems with reliability and/or operating limits were and continue to be of major engineering concern.

The Orbiter Auxiliary Power Unit (APU) currently operates with electric resistance line heaters which are controlled with thermostats. A design option simplification of this heater subsystem is being considered which would use self-regulating heaters. A determination of the properties and thermal operating characteristics of these self-regulating heaters was needed.

The Orbiter fuel cells are cooled with a Freon loop. During a loss of external heat exchanger coolant flow, the single pump circulating the Freon is to be left running. It was unknown what temperature and flow rate transient conditions of the Freon would provide the required fuel cell cooling and for how long.

OBJECTIVE

The overall objective of the proposed work was the development of the thermal characterization and subsequent analysis of both the proposed self-regulating APU heater and the fuel cell coolant loop subsystem. The specific objective of the APU subsystem effort was to determine the feasibility of replacing the current heater and thermostat arrangement with a self-regulating heater. The specific objective of the fuel cell coolant subsystem work was to determine the transient coolant temperature and associated flow rates during a loss-of-external heat exchanger flow.

PART I: SELF-REGULATING HEATER

The orbiter Auxiliary Power Unit (APU) currently uses electric resistance heaters controlled by thermostats to heat the fuel and exhaust lines. Keeping these lines at an elevated temperature is necessary to prevent freezing and subsequent blockage of the lines, especially when the APU is on stand-by during a space operation and the system is exposed to space vacuum and low temperature conditions.

For reliability, the line heaters and thermostats are "doubled-up" for each heated line, thus increasing the system complexity. It is also necessary to have a large sensing subsystem operating to ensure the heaters and thermostats are all operating. In order to reduce the complexity of both the heater-thermostat subsystem and the sensing subsystem, it was proposed to investigate resistance heaters which are self-regulating (self-limiting) to maintain a given temperature.

BACKGROUND THEORY

Many materials exhibit the feature of increasing electrical resistance with increasing temperature; however, the change in resistance is usually fairly small for small (tens of degrees) temperature changes. RAYCHEM Corporation has developed an irradiated polymer material which exhibits order of magnitude electrical resistivity increases with a 10°C increase (in the range of room temperature).

This RAYCHEM material has been proposed as a self-regulating or self-limiting electrical resistance heater. The heater is composed of two electrically-conductive "bus bar" wires on either side of the self-limiting material (irradiated polymer), with a voltage difference applied across the two wires. As shown in Figure 1, the wires and self-limiting material are encased in an insulating material.

The self-limiting resistance heater works on the same principle as other resistance heaters. That is, the heating power is given by:

$$\text{Heating Power} = I^2 R, \quad (1)$$

where I is the current and R the electrical resistance. As shown in Figure 2, a voltage (V) is applied across the "bus bar" wires, and the current that flows through the self-limiting material is determined by the material's resistance (which is a function of the material's temperature) as determined by the relation:

$$V = IR. \quad (2)$$

By substituting, the heating power can be expressed as a function of the applied voltage and the material's resistance:

$$\text{Heating Power} = V^2 / R \quad (3)$$

Thus, with the resistance directly related to temperature, it is seen that the heating power will vary inversely with the temperature of the heater: high power at low temperatures, low power at high temperatures.

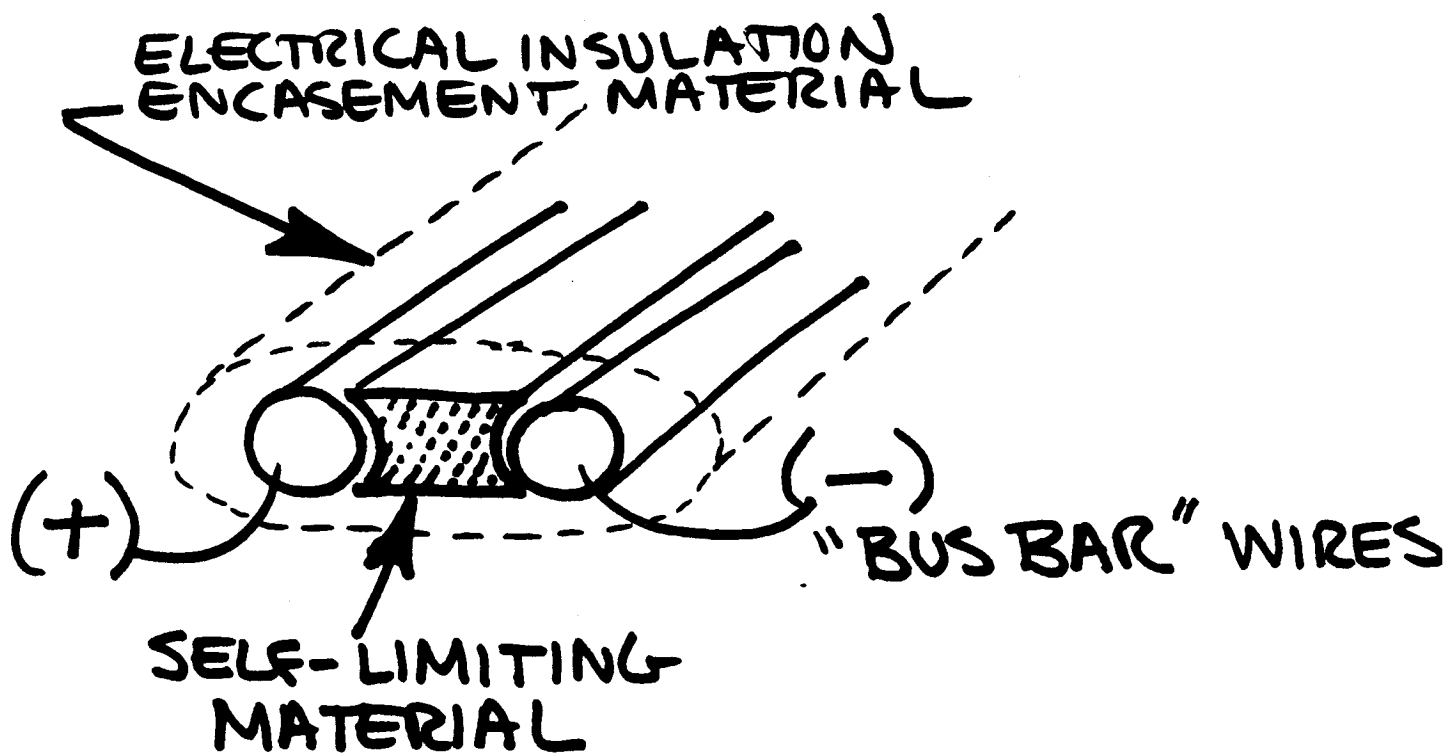


Figure 1. Schematic of RAYCHEM Corporation self-limiting electrical resistance heater.

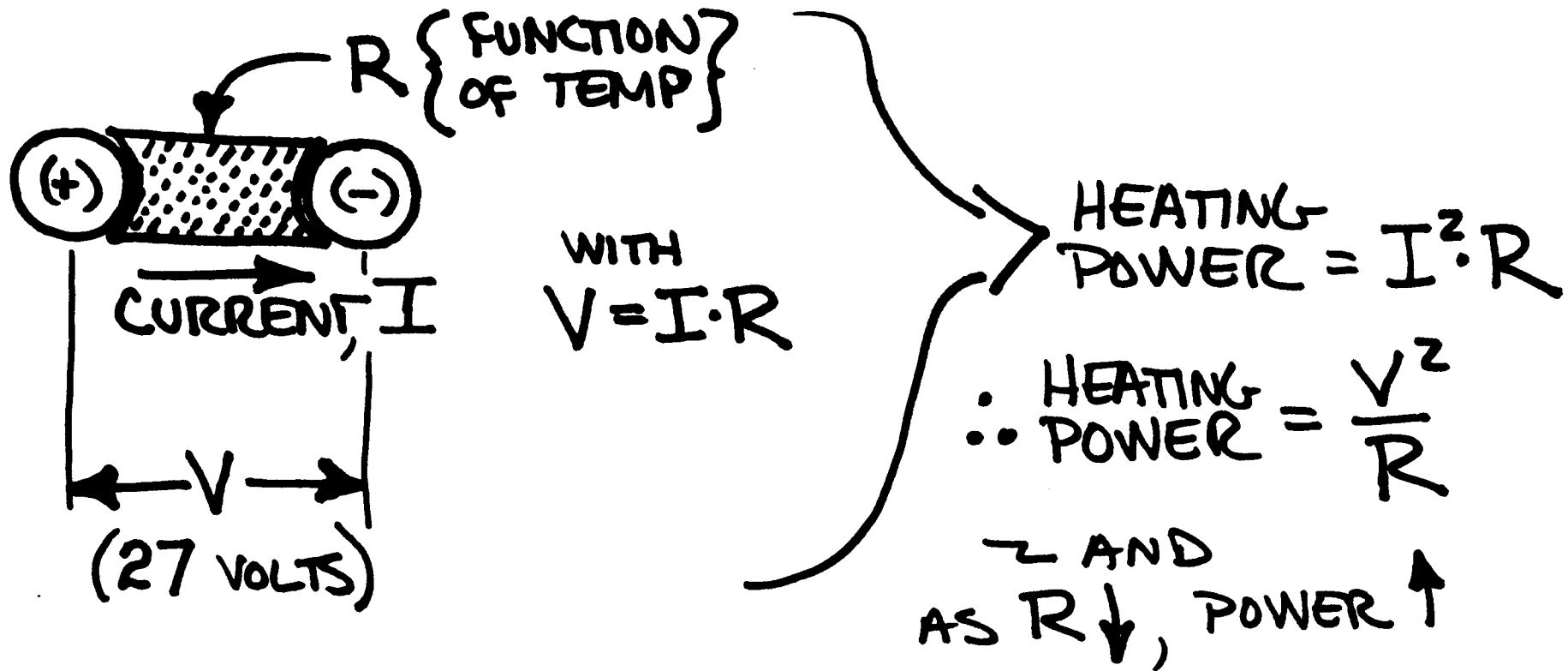


Figure 2. The equations involved in the heating power illustrating the inverse relationship between resistance (temperature) and heating power.

The material appears "programmed" with a built-in rheostat which causes the material to behave as if it were thermostatically controlled. If an environment existed which caused the heater's temperature to decrease, the heater power would increase, which would cause the heater temperature to increase. The heater temperature would finally stabilize at the point where the heater power equalled the heat loss from the heater. The key to this self-regulating heater is that the resistance, and thus heater operating range, varies from very low to very high values over a very small temperature range. Thus, the heater maintains its own temperature within a small range regardless of environmental temperature; this is the "thermostat-less" control desired.

TEST RESULTS

As discussed, the key to this self-limiting heater concept is a large resistance change over a small temperature range. A sample of the self-regulating heater was obtained and a series of tests were run with the following objectives:

- Demonstrate the self-limiting feature of the heater to reach equilibrium (room temperature range);
- Determine the heater power generated per unit length as a function of heater temperature; and
- Determine the material's electrical resistivity as a function of the material's temperature.

The experimental set-up is shown in Figure 3 where the heater was placed inside the environmental chamber taped to an aluminum block which acted as a thermal source/sink for the heater. Thermocouples were attached external to the encasement material and thus did not actually measure the temperature of the temperature-resistance material itself. A DC power supply applied a constant 27 volts to the heater (RAYCHEM instructions) and the amps were recorded when the heater was energized.

Self-limiting Equilibrium Test

The first test performed was to see if the heater wire would actually "self-limit". The test consisted of placing the heater wire (attached to the aluminum block) into the environmental chamber which was set at 32° F (0° C). After the heater wire and block were chilled to 32° F and in equilibrium with the chamber, the heater was energized.

As is shown in Figure 4, the temperature of the heater rose with time and reached a "self-limit" of 37.5° F after 5 minutes. The power of the heater at this condition was 10W per foot of length. Thus, the heater demonstrated the ability for "self-limiting heating".

Heater Power versus Temperature Test

The above test at one specific temperature provided the power output of the heater for a given heater temperature (10W at 37.5° F).

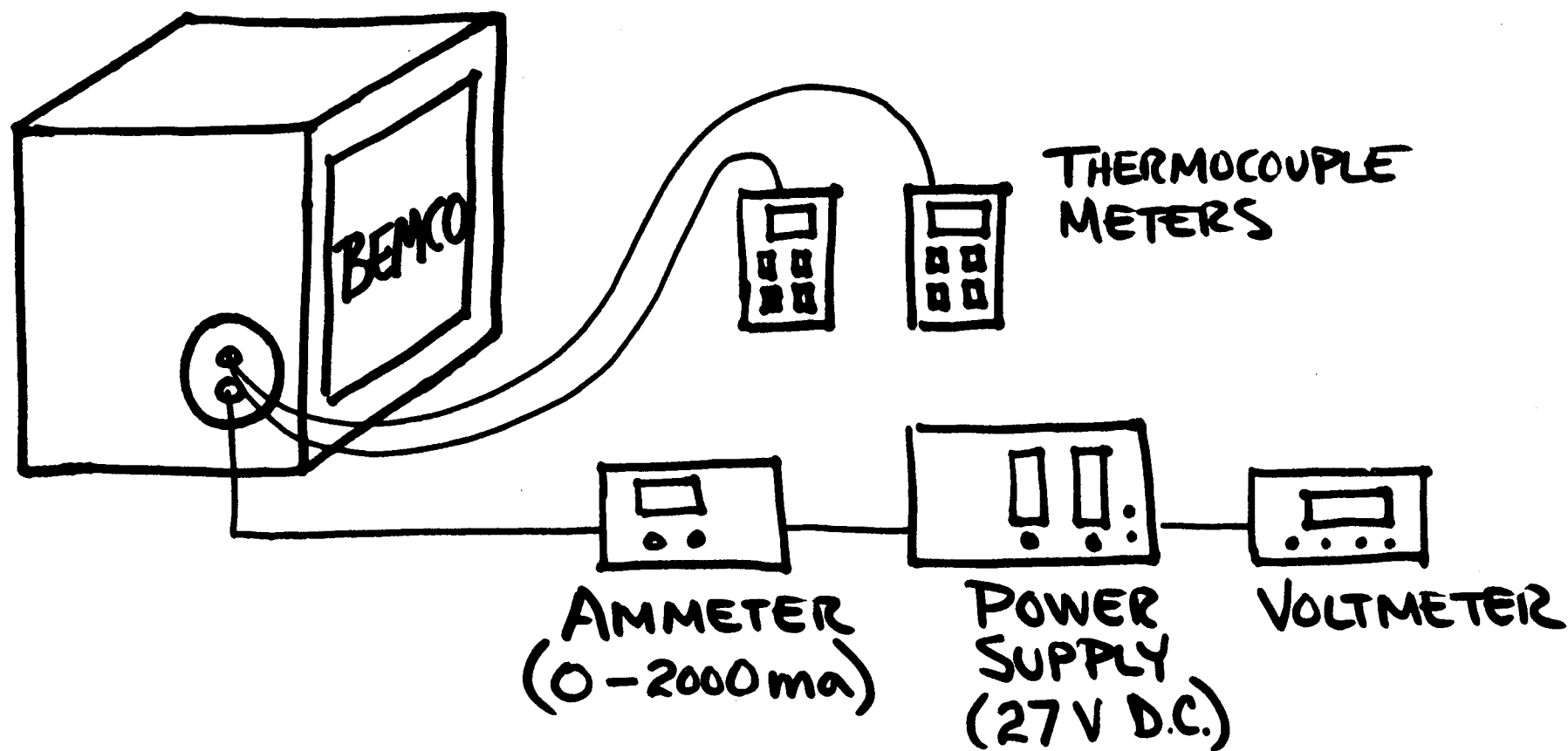


Figure 3. A schematic of the experimental test set-up. The BEMCO environmental chamber is located in BLDG. 352.

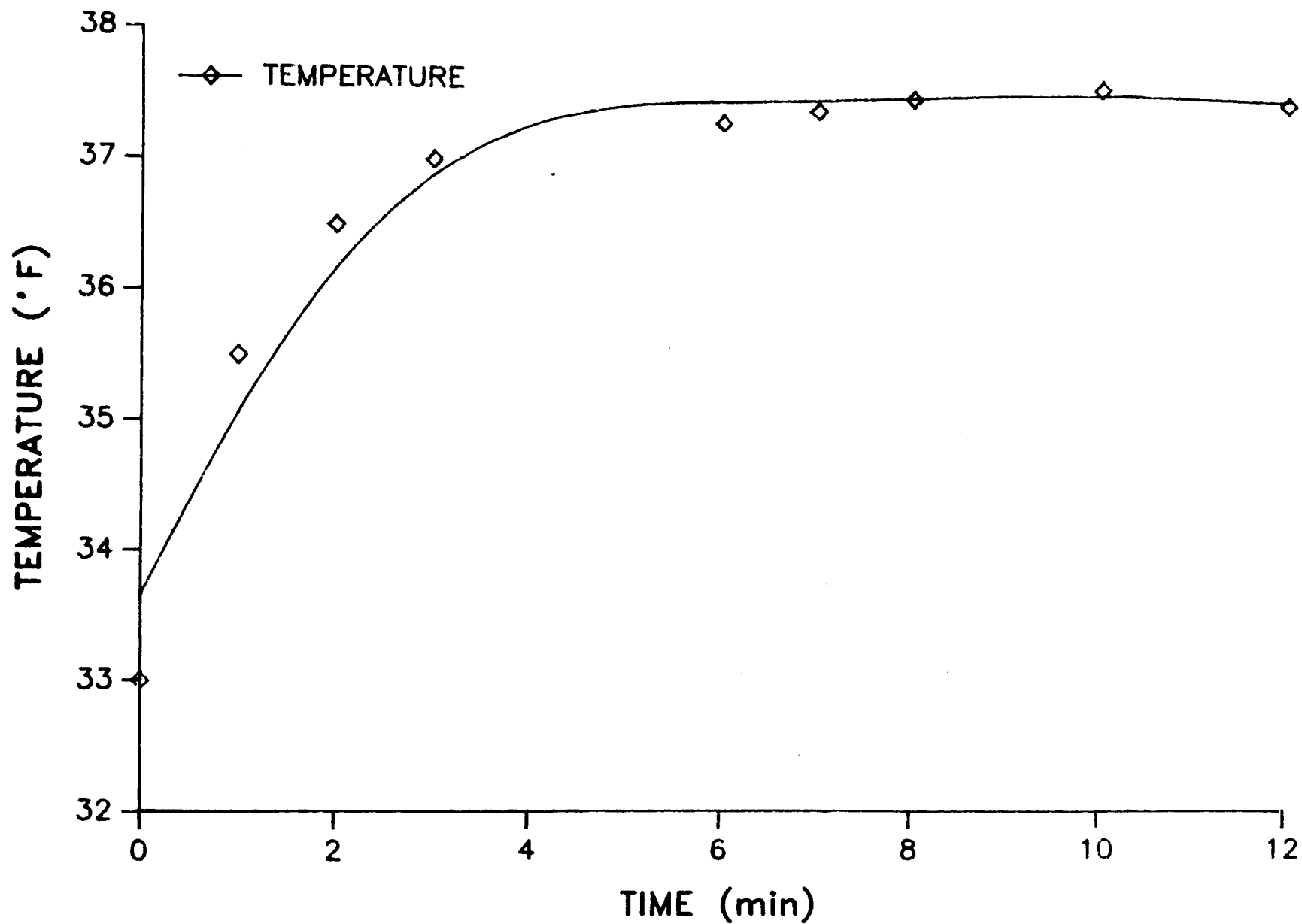


Figure 4. Results of initial self-limiting equilibrium test with environmental chamber at 32° F (0° C).

For engineering design purposes with this particular heater, it is necessary to know the heater power over a range of heater temperatures.

By performing the above described equilibrium test with a range of environmental chamber temperatures, the heater power performance as a function of heater temperature was determined by measuring the equilibrium current for each temperature. Figure 5 presents this heater performance information. It should be noted that the power performance curve shown is specific to the particular heater wire (geometry, dimensions, encapsulation material, etc.) tested.

Electrical Resistivity Determination

In order to use the power versus temperature information derived from the above test, it is necessary to derive a more general, non-design specific material property. Electrical resistivity is the material property which will allow the design of other heater geometries with other power levels for a given temperature.

The resistivity of the self-limiting material was calculated from the voltage and current measurements made when the heater reached equilibrium at a given temperature. The resistance was calculated using Equation 2, and then the resistivity was determined using the equations in Figure 6 and the heater dimensions. The result of these calculations at various temperatures is presented in Figure 7. The resistivity variation over a 50° F (28° C) range is seen to be two orders of magnitude.

CONCLUSIONS

The tests and calculations demonstrate that the RAYCHEM material has the electrical resistivity temperature dependence necessary to act as a self-limiting (self-thermostated) resistance heater. Use of this heater could lead to significant reductions in heater and associated sensing subsystems complexity.

The determination of the resistivity curve allows the physical design of heaters with power characteristics determined from thermal loss calculations for specific applications. It is recommended that the operating characteristics of this self-limiting heater be examined when applied to a transient environmental and internal load, such as an insulated APU fuel line during start-stop operations.

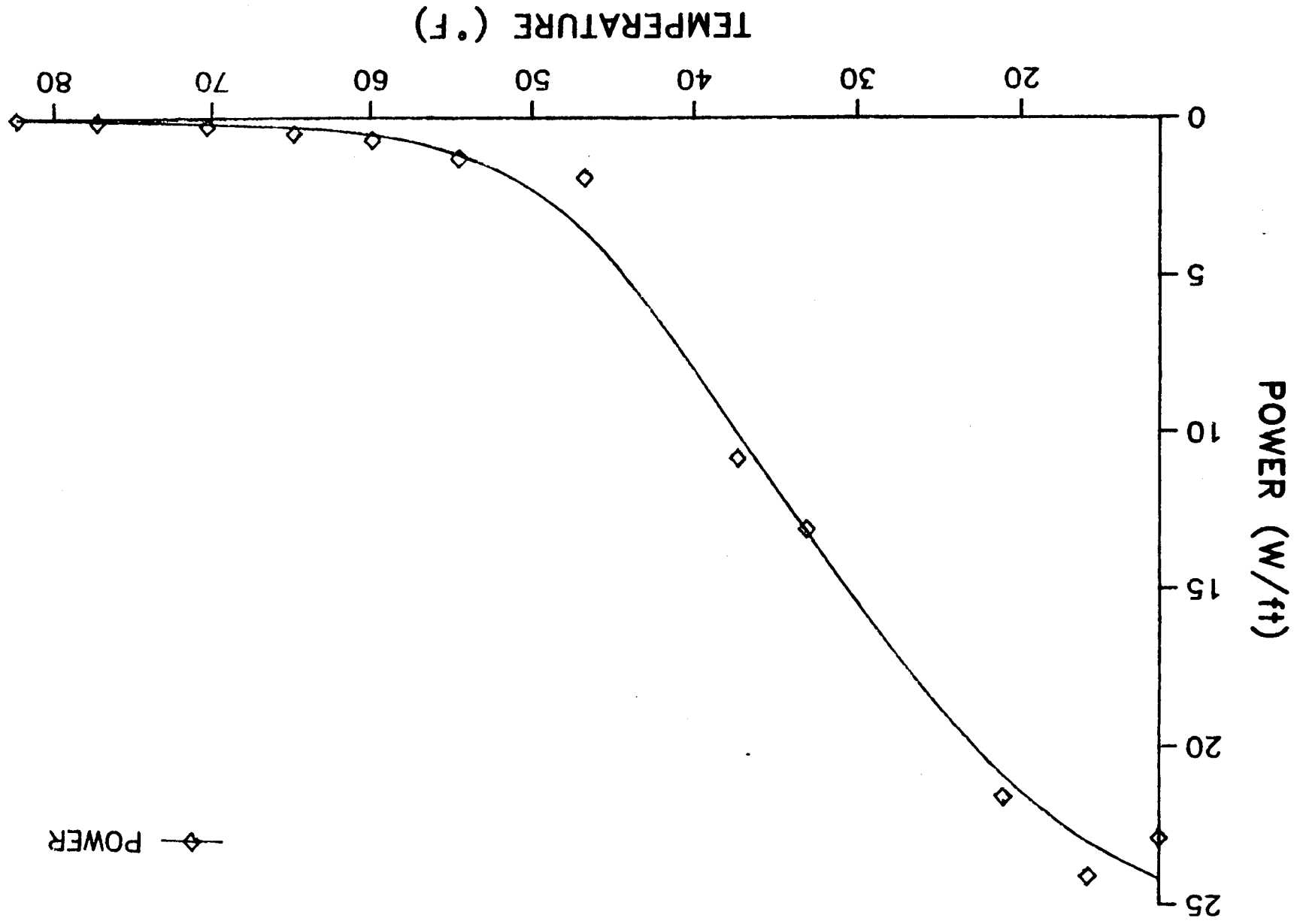


Figure 5. Heater power developed per foot of length as a function of heater temperature for the specific heater tested.

MATERIAL ELECTRICAL RESISTIVITY (ρ)
 DETERMINED AS A FUNCTION OF
 MATERIAL TEMPERATURE (USEFUL
 FOR DESIGN OF FUTURE HEATERS)

$$\frac{\rho \cdot L}{A} = R$$

WHERE

L = DISTANCE BETWEEN WIRES

A = CROSS-SECTIONAL AREA
 ($t \times 1 \text{ FOOT}$) CURRENT
 FLOWS THROUGH

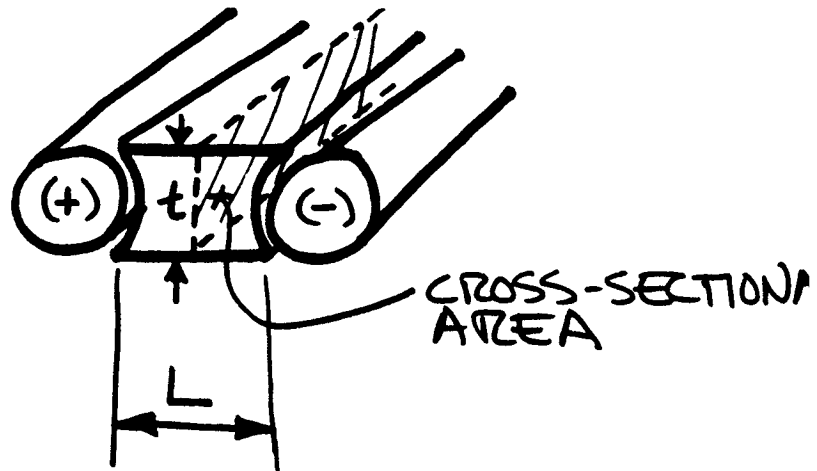


Figure 6. Electrical resistivity relationship to material electrical resistance and heater geometry.

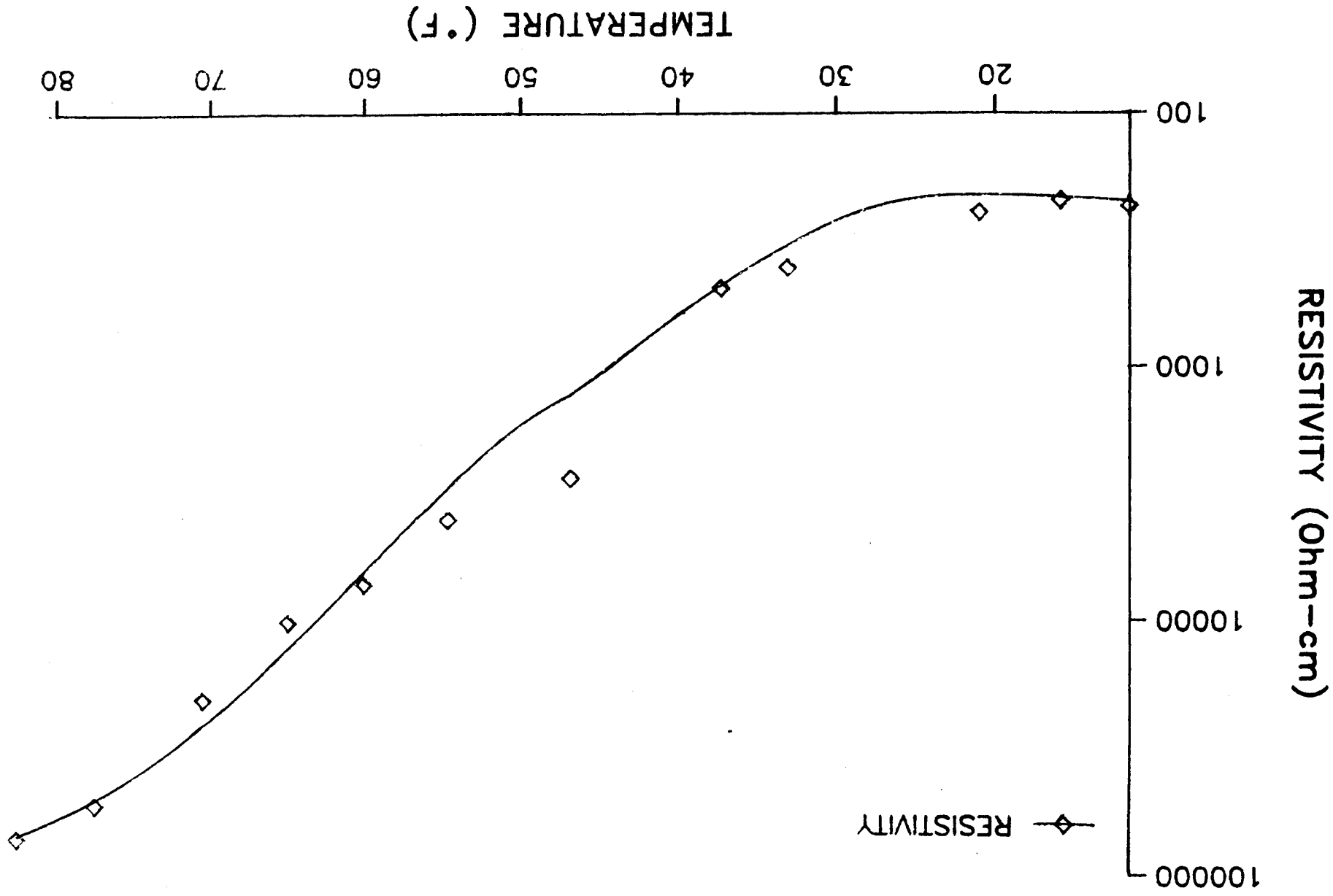


Figure 7. Material resistivity as a function of its temperature.

PART 2: FUEL CELL COOLANT SYSTEM

The Orbiter fuel cell powerplants generate heat and operate at the proper temperature via cooling with a circulated coolant (FC4O). This circulating coolant rejects the fuel cell heat to the Orbiter cooling system through an external heat exchanger. The question has been posed as to how long the fuel cell power plant could operate if the Orbiter cooling system failed and could not be used as the heat sink. With the loss of the heat sink, the fuel cell would ultimately reach a high enough temperature that it would be unsafe to continue operating it. However, it was unknown how long it would be possible to operate the fuel cell before reaching an unsafe operating temperature.

FUEL CELL TESTS

Testing for the loss-of-coolant accident profile with a fuel cell powerplant was performed at NASA-Johnson in 1987-88. The tests were run at TTA using a prototype 2-stack powerplant, not the Orbiter 3-stack system. Additionally, the TTA tests did not try to exactly match the external heat exchanger/Orbiter cooling system layout as is found on the Orbiter.

A series of tests were run where the loss-of-cooling temperature transients were examined for various operating power levels, both before and after the loss-of-coolant. Several of the fuel cell coolant system temperatures were monitored during the accident transients, with the fuel cell being operated until the temperature of the coolant leaving the stack (STKOUT) reached 250° F. Appendix A contains tabular and graphical data from some of these 2-stack fuel cell tests.

PROBLEM AND APPROACH

Even after the testing of the 2-stack fuel cell powerplants, it was still unknown how long an Orbiter 3-stack fuel cell powerplant could be operated safely without the heat sink. It also was not possible to test a 3-stack system as a "spare" powerplant did not exist. Thus, some method had to be developed to relate the 2-stack test data to 3-stack system response to loss-of-cooling.

The approach used was to develop a computer simulation and simulate the accident transient performance characteristics of the Orbiter fuel cell powerplant coolant system. The computer model of the coolant system was to be verified/validated by the following:

- 1) Comparing steady-state simulation results for a 2-stack fuel cell with the manufacturer's (IFC) 2-stack computer model results;
- 2) Comparing to the TTA transient test results on the 2-stack system (Appendix A); and
- 3) Comparing to the Orbiter 3-stack system steady-state values.

Only after the computer model successfully simulated the above three situations would be simulation of the 3-stack Orbiter system transient performance to performed the reported.

THE MODEL

The computer model of the coolant system involved almost all major subsystems of the fuel cell power plant. The schematic of the Orbiter fuel cell power plant is shown as Figure 8, with the coolant system on the right hand side of the figure. It can be seen that the coolant system is directly linked thermally to five major components: (1) the fuel cell, (2) the H_2 and O_2 preheater heat exchangers, (3) the external heat exchanger (the heat sink), (4) the condenser for the H_2 and H_2O mix leaving the fuel cell, and (5) the startup/sustaining heaters (not used during the loss-of-coolant accident).

The flow rates of H_2 , O_2 , and coolant, the masses and heat capacities of all components, and the thermostated and/or pressure controlled operating modes, all had to be found, both for the Orbiter 3-stack and 2-stack test systems. Much of the data can be found in the manual United Technologies FCR-0216, dated 9 April 1976.

The computer model is named FCPSIM (fuel cell power plant simulation) and a complete listing is given in Appendix B. The code is fairly well documented using internal comments, and the various temperatures, rates of heat transfer, flow rates, and other operating conditions are listed and defined. The computer code has been fitted with an interactive input format with nine parameters to be set (or default value used):

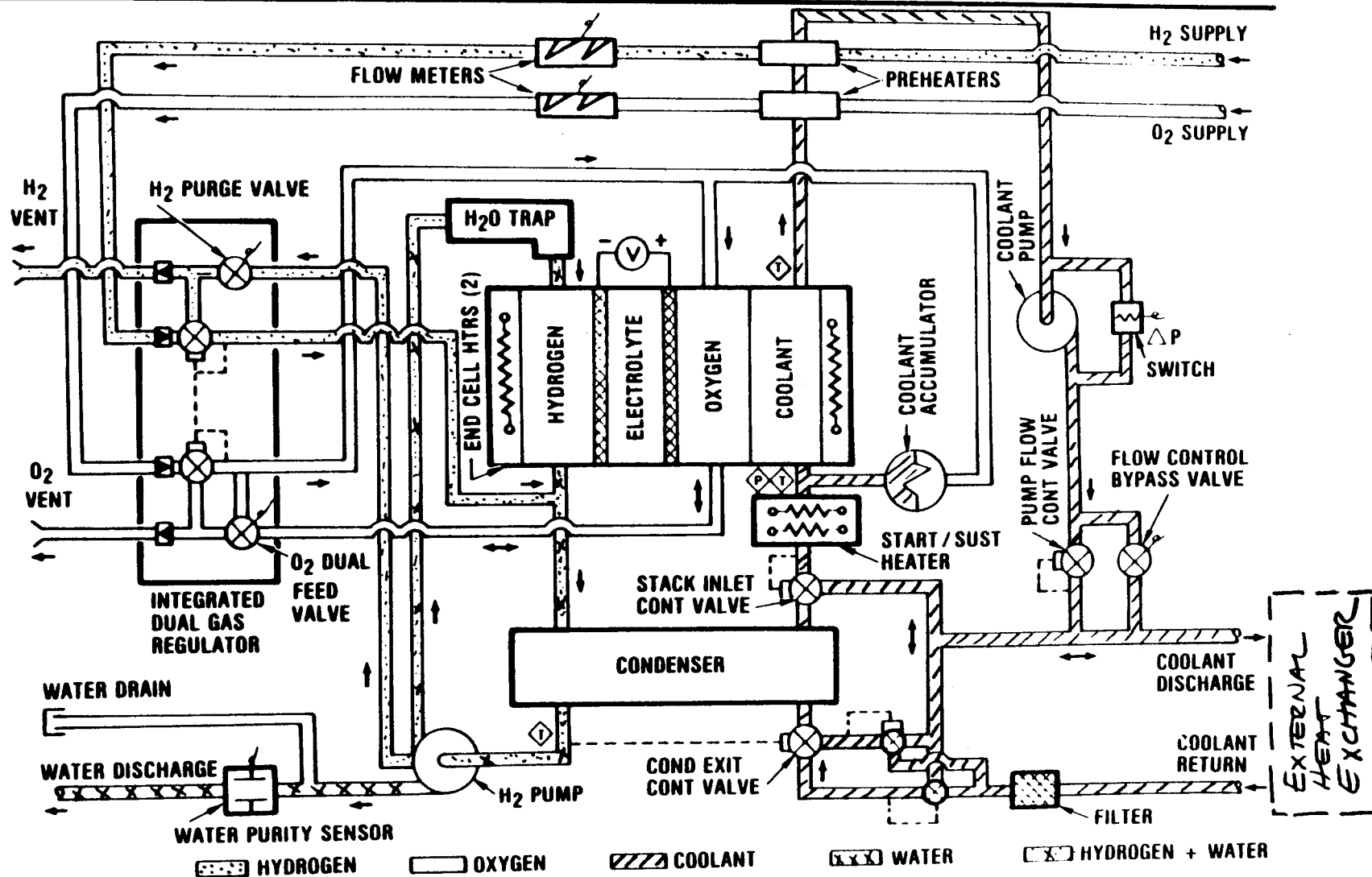
- 1) Fuel cell power level (in watts)
- 2) Fuel cell type (2-stack or 3-stack)
- 3) O_2 supply flow rate (pounds per hour)
- 4) O_2 supply temperature (in $^{\circ}F$)
- 5) H_2 supply flow rate (pounds per hour)
- 6) H_2 supply temperature (in $^{\circ}F$)
- 7) Environmental temperature (in $^{\circ}F$)
- 8) Environmental condition (vacuum or air)
- 9) External heat exchanger temperature ($^{\circ}F$)

Figure 9 is a listing of this interactive input format with default values shown in parentheses, the choice of fuel cell power of 4100 watts, the simulation system time step chosen as 10 seconds, and the printout time step chosen as 300 seconds. The output data file (FCPSIM.OUT) format is presented in Figure 10 and shows the various system parameters which are calculated by the program. The output data acronyms are listed and defined within the code, as previously mentioned.

SIMULATION RESULTS

As described earlier, the verification of FCPSIM involved comparisons with manufacturer's code results for both 2- and 3-stack system, and 2-stack transient test results. The 2-stack comparisons, steady-state and transient, were able to be done, but the 3-stack

Orbiter Fuel Cell Powerplant



87SSV195894

Figure 8. Schematic of the Orbiter fuel cell power plant with the coolant loop on the right-hand side.

Last interactive login on Thursday, 18-AUG-1988 17:56

*** ALL-IN-1 MAIL ON NODE PFD FOR MOREHOUSE_JEFF_PFD ***
0 ALL-IN-1 Mail Message(s) Waiting!

run FCPSIM

SELECT OPTION TO UPDATE

- 1: FC POWER (1999.56)
- 2: FC TYPE (1="OLD")
- 3: O2 SUPPLY FLOW RATE (1.33) ← PPH
- 4: O2 SUPPLY TEMPERATURE (-200) ← °F
- 5: H2 SUPPLY FLOW RATE (0.168)
- 6: H2 SUPPLY TEMPERATURE (-300)
- 7: ENVIRONMENTAL TEMPERATURE (50.0)
- 8: ENVIRONMENTAL CONDITION (0="VACUUM")
- 9: EXTERNAL HEAT EXCHANGER TEMPERATURE (90.0)

HIT RETURN WHEN FINISHED TO EXECUTE PROGRAM

1
ENTER FUEL CELL POWER IN WATTS

4100.

- SELECT OPTION TO UPDATE

- 1: FC POWER (1999.56)
- 2: FC TYPE (1="OLD")
- 3: O2 SUPPLY FLOW RATE (1.33)
- 4: O2 SUPPLY TEMPERATURE (-200)
- 5: H2 SUPPLY FLOW RATE (0.168)
- 6: H2 SUPPLY TEMPERATURE (-300)
- 7: ENVIRONMENTAL TEMPERATURE (50.0)
- 8: ENVIRONMENTAL CONDITION (0="VACUUM")
- 9: EXTERNAL HEAT EXCHANGER TEMPERATURE (90.0)

HIT RETURN WHEN FINISHED TO EXECUTE PROGRAM

ENTER CALCULATION TIME STEP SIZE IN SECONDS

10.

ENTER PRINTOUT TIME STEP SIZE IN SECONDS

300.

FORTRAN STOP

ED FCPSIM.OUT

1 FUEL CELL WATTS: 4100.0 2 SUBSTACK VACUUM

*

FCPSIM INTERACTIVE
INPUT FORMAT

OLD IS "2 STACK"
NEW IS "3 STACK"

DEFAULT VALUES
IN ()

OUTPUT FILE

Figure 9. The FCPSIM interactive input format listing.

FCPSIM.OUT

FUEL CELL WATTS: 4100.0 2 SUBSTACK VACUUM
 O2 SUPPLY FLOW RATE(LB/HR): 1.33 O2 SUPPLY TEMPERATURE (DEG F): -200.0
 H2 SUPPLY FLOW RATE (LB/HR): 0.168 H2 SUPPLY TEMPERATURE (DEG F): -300.0
 ENVIRONMENTAL TEMPERATURE (DEG F): 50.0
 EXTERNAL HEAT EXCHANGER TEMPERATURE (DEG F): 90.0

TIME	TSKO	TFC	QGEN	QCFC	QFCEN	QFCRE	CURR	VFC	TOPHC
T02OUT	QPHO2	QPHOEN	TH2OUT	TOPHH	QPHH2	QPHHEN	TCP	QCFEN	WC
WCB1	WCB2	WCEHX	WCC	TEHX	QH Xen	QEHX	TCE	QCVEN	WCC
TCCO	QCOND	QCDEN	THI	WH2T	TMIX	TCCI	TSKIN	QSSHEN	
5.00	197.8	200.7	4010.7	1746.0	13.9	1816.1	134.0	30.6	195.1
158.0	252.6	48.8	145.6	189.7	594.2	24.8	192.2	128.1	425.0
103.0	105.3	216.7	322.0	90.0	62.9	-5972.6	151.4	55.6	322.0
180.7	5138.0	107.5	199.0	10.6	183.5	122.8	182.6	104.3	
10.00	199.2	202.1	3999.8	1906.0	14.1	1869.4	133.9	30.6	196.5
159.3	253.4	49.4	146.9	191.1	595.5	25.1	193.5	129.8	425.0
103.0	100.7	221.3	322.0	90.0	62.9	-6182.6	151.4	54.6	322.0
180.2	5190.4	108.9	200.4	10.6	183.5	121.7	182.6	104.3	

Figure 10. Example listing of FCPSIM.OUT data listing for two times (5 minutes and 10 minutes).

comparison was not done since manufacturer's data could not be obtained. The results of simulations with the 2-stack and 3-stack system parameters is presented below.

Steady-state 2-stack Comparison

The initial comparison was between the FCPSIM code and the manufacturer's code (IFC) for steady-state operation of the 2-stack fuel cell power plant. Figure 11 presents the side-by-side comparisons for various system parameters, both for low power (2 kw) and high power (12 kw) operation. Very good agreement is seen in almost all areas except for the coolant flow through the condenser. This coolant flow "problem" in the condenser was never satisfactorily understood or reconciled.

Transient 2-stack Comparison

Figures 12, 13, and 14 present the comparisons between the transient temperatures predicted by FCPSIM code and those measured in the TTA tests and a 2-stack fuel cell power plant operating at 4.1 kw, 3 kw, and 2.5 kw, respectively. Good agreement was produced except at the lowest power levels (2.5 kw and below). The major problem appears to lie in the extremely small amount of excess heat generated by the fuel cell, which causes large variations in the temperature changes over time. Alternately, the thermal capacitance of the external heat exchanger may be chosen as being larger than it "actually" appears.

The initial (5 to 10 minutes) variations in FCPSIM temperatures STKIN and TCE arise from the previous problem of controlling/providing the proper flow through the condenser.

Purge Flow

It is possible to send a large H_2 flow at low temperature through the fuel cell. This low temperature flow is exhausted (purged) overboard and acts as a supplementary fuel cell coolant system. Figure 15 shows the significant effect this purge flow can have on extending the operating time for a given fuel cell power level, from less than 30 minutes to over 45 minutes with purge.

CONCLUSIONS

The FCPSIM code simulating the fuel cell power plant coolant system appears to work well at fuel cell power levels above 3 kw, but below this level the code does not agree with transient test data well. Further investigation is warranted since the lower power levels would be expected to be used if an accident involving the coolant sink did occur. Also, the 3-stack steady-state FCPSIM code to IFC code still remains to be done.

Of particular note is the fact that using "purge" flow rates with the fuel flows would significantly extend the operational time of the fuel cell during a coolant loss transient.

2 kW Power		12 kW Power	
* IFC Code	FCPSIM	* IFC Code	FCPSIM
FUEL CELL CURRENT VOLTAGE	63.26 31.61	423.2 28.36	428.5 28.3
COOLANT TEMPS (°F)			
STACK OUT (STKO)	185.6	223.7	229.6
AFTER PUMP	183.5	217.8	220.5
CONDENSER IN	113.2	125.0	142.6
MIXING VALVE	183.2	183.5	188.2
STACK IN (STKIN)	180.7	183.3	187.8
HYDROGEN TEMPS (°F)			
CONDENSER IN (TCE)	185.1	216.5	232.3
CONDENSER OUT (TCE)	151.7	151.7	151.0
HEAT TRANSFER (BTU/Hr)			
CONDENSER EXTERNAL HX	2,854	12,849	13,726
COOLANT FLOWS (Pounds/Hr)			
CONDENSER EXTERNAL HX	2,922	23,921	23,143
CONDENSER EXTERNAL HX	149.8	885.0	1100.0
	111.2	650.8	654.5

* REFERENCE: UNITED TECHNOLOGIES FCIR-0216
9 APRIL 1976

Figure 11. Comparison of results from steady state FCPSIM code to IFC code (manufacturer) for the 2-stack fuel cell power plant at low (2 kw) and high (12 kw) power.

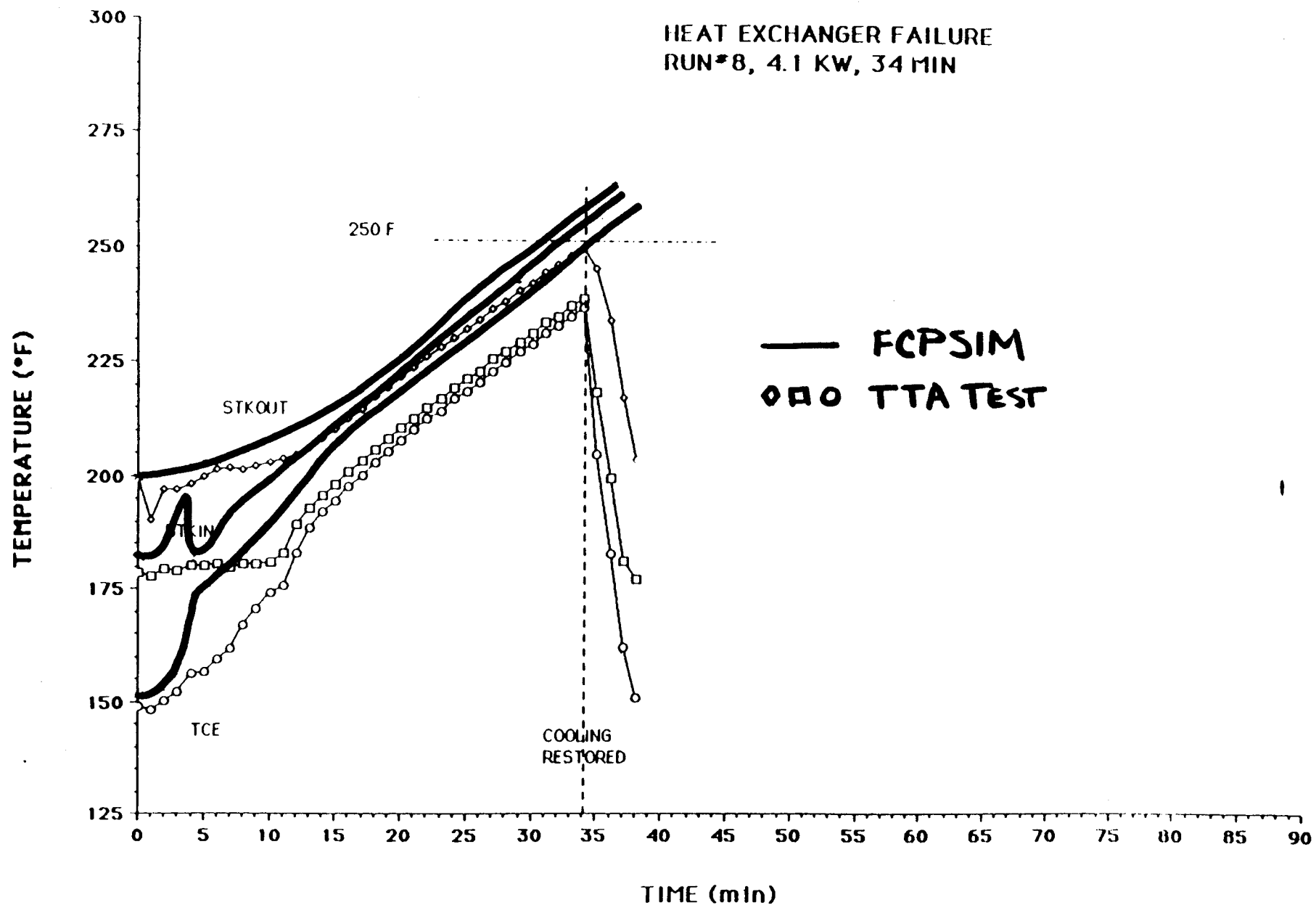


Figure 12. Comparison of transient temperatures from FCPSIM code and TTA test for 2-stack system at 4.1 kw with loss of external cooling sink.

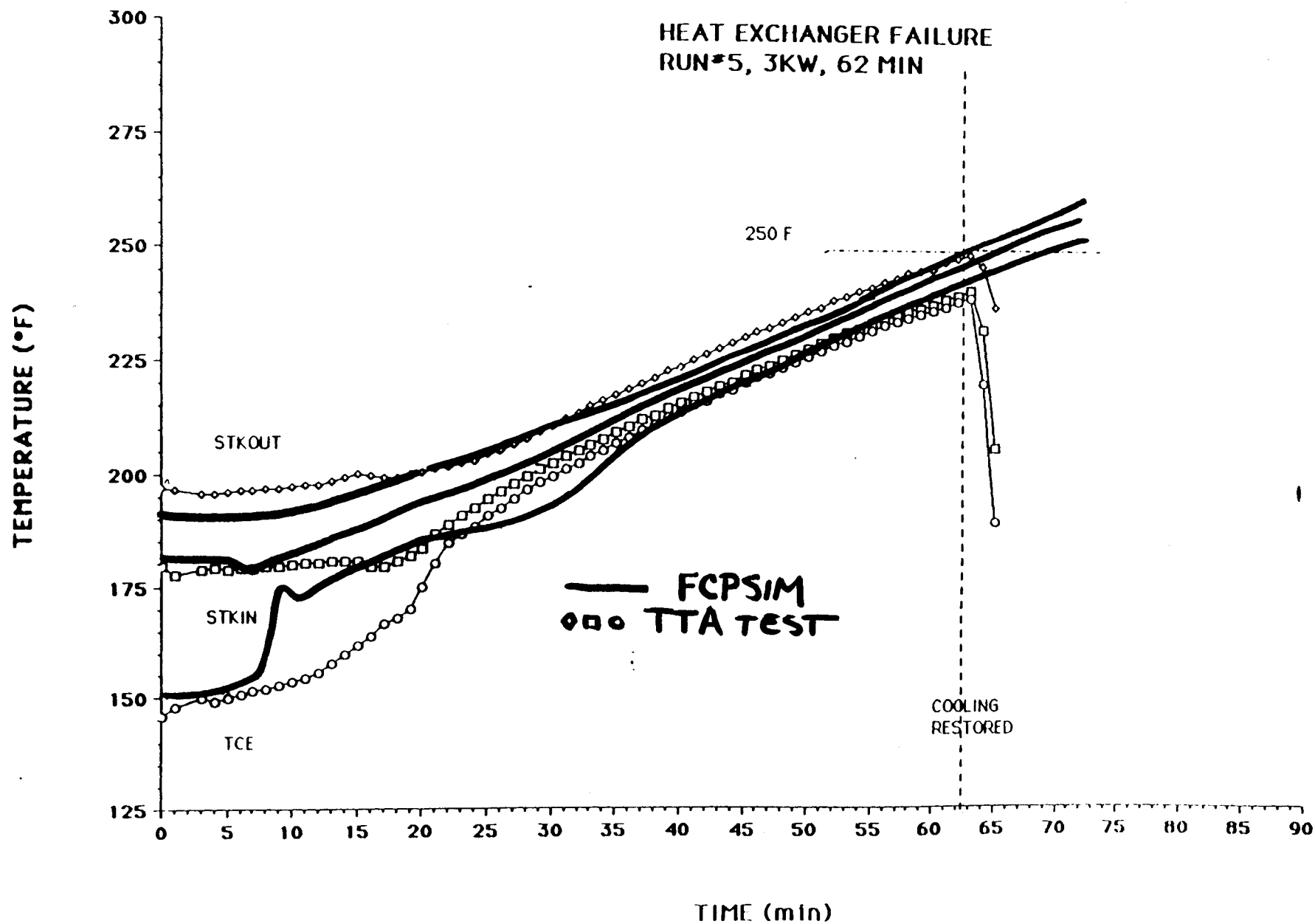


Figure 13. Comparison of transient temperatures from FCPSIM code and TTA test for 2-stack system at 3 kw with loss of external

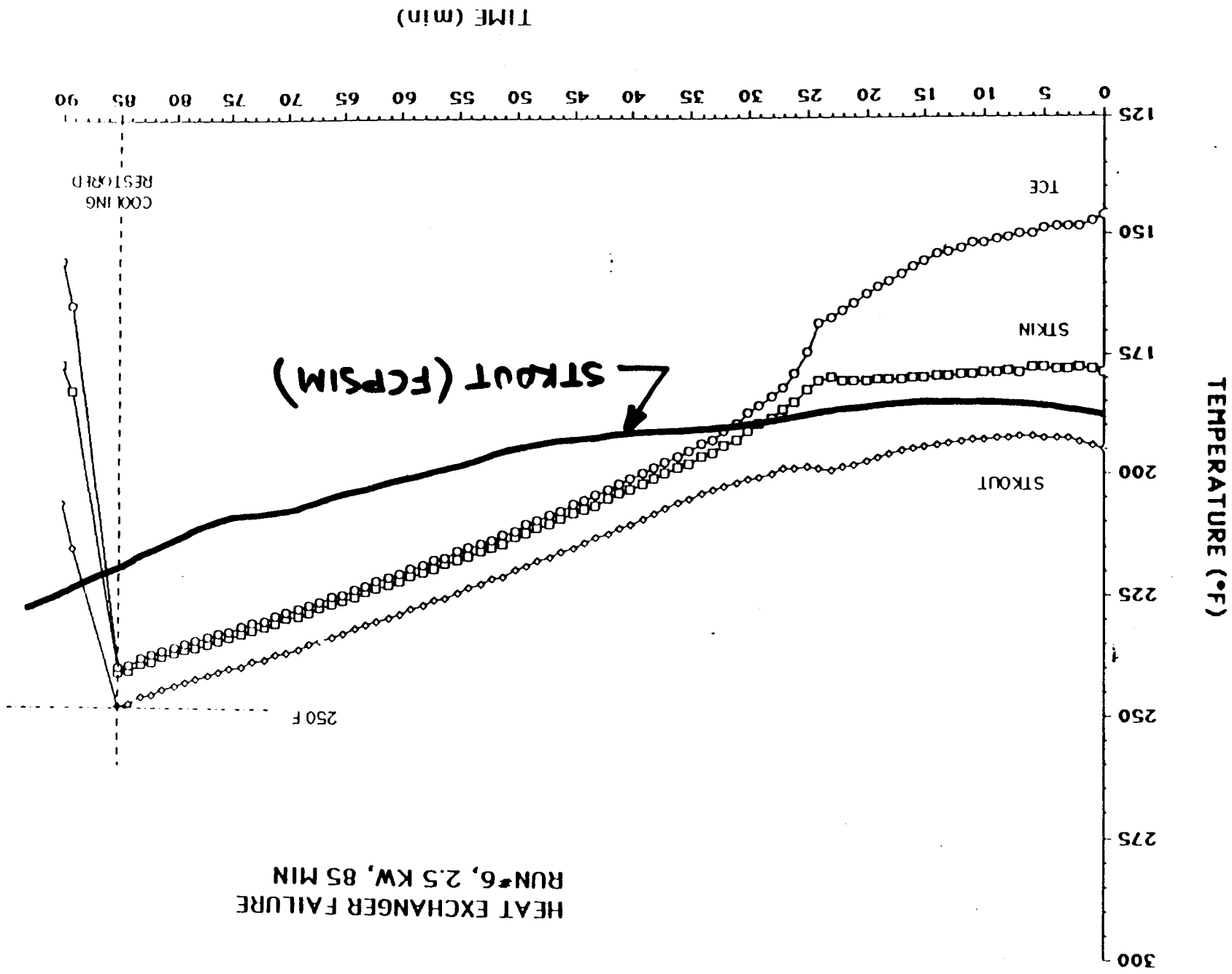


Figure 14. Comparison of transient temperatures from FCPSIM code and TTA test for 2-stack system at 2.5 kw with loss of

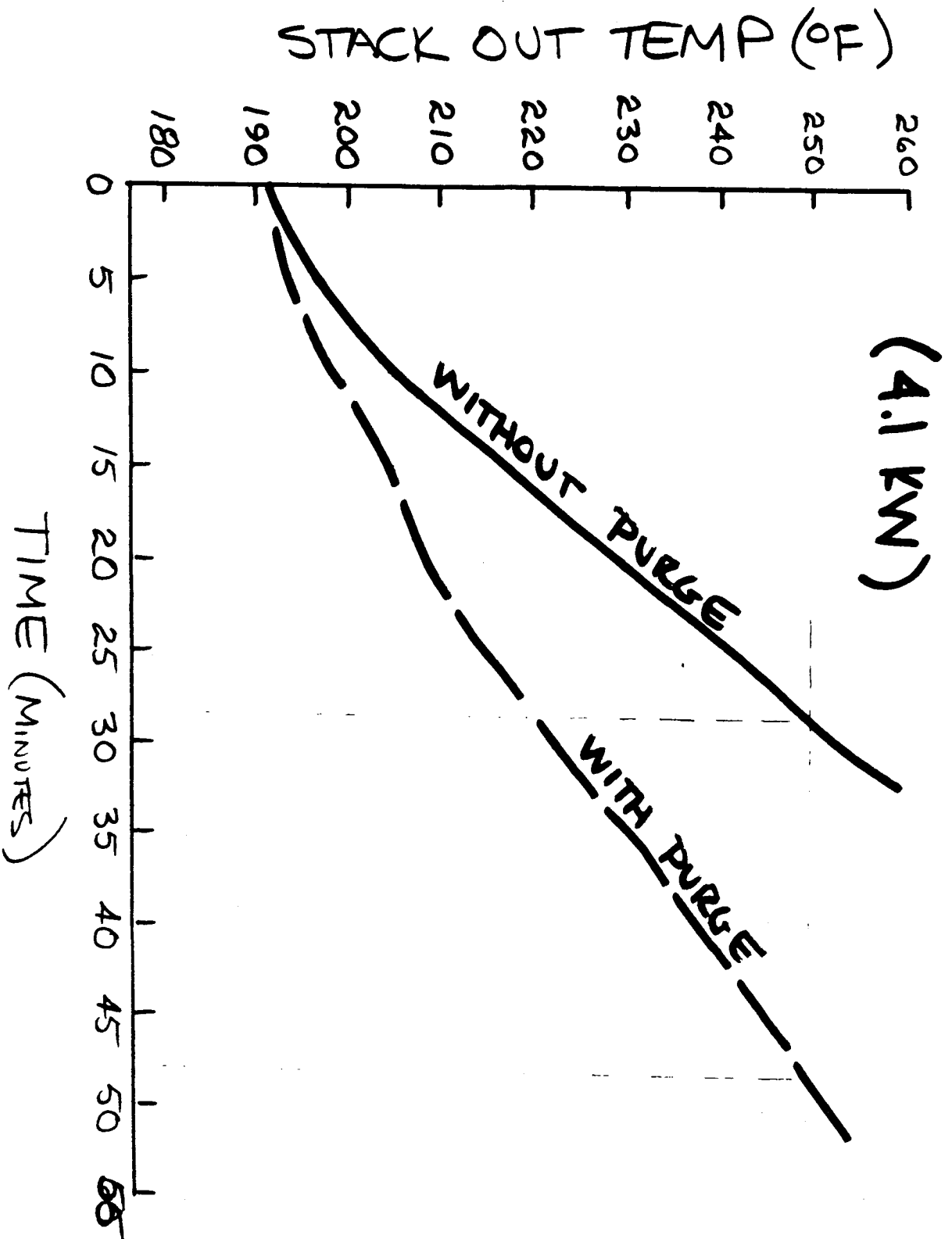


Figure 15. Comparison of transient stack-out temperatures for 3-stack system with and without purge during loss of external cooling sink at 4.1 kw (using FCPSIM code).

APPENDIX A:
NASA FUEL CELL TEST DATA

X-708 DATA

	A	B	C	D	E	F
1			2.5 KW			
2	TIME	STK IN	STK OUT	TCE		
3	(MIN.)	(DEG. F)	(DEG. F)	(DEG. F)		
4	0	178.70	195.00	146.20		
5	1	178.20	194.00	147.20		
6	2	177.90	193.30	148.40		
7	3	178.20	192.80	148.40		
8	4	178.20	192.60	148.40		
9	5	177.90	192.60	148.60		
10	6	177.90	192.30	149.90		
11	7	178.70	192.30	149.90		
12	8	178.40	192.60	150.60		
13	9	178.70	192.80	151.10		
14	10	178.90	193.10	151.80		
15	11	179.10	193.10	151.80		
16	12	179.40	193.30	152.80		
17	13	179.60	193.80	153.50		
18	14	179.60	194.30	154.20		
19	15	180.10	194.50	155.50		
20	16	180.10	195.00	156.90		
21	17	180.40	195.30	158.20		
22	18	180.40	196.00	159.60		
23	19	180.40	196.70	161.10		
24	20	180.60	197.50	162.50		
25	21	180.90	198.40	164.30		
26	22	180.60	198.90	165.70		
27	23	180.10	199.40	167.40		
28	24	180.90	199.20	168.70		
29	25	182.60	198.90	174.80		
30	26	185.30	199.20	179.10		
31	27	187.00	199.20	182.30		
32	28	188.70	200.10	184.30		
33	29	190.10	200.90	186.20		
34	30	191.40	201.40	187.70		
35	31	193.30	202.10	189.90		
36	32	194.50	202.80	191.40		
37	33	196.00	203.60	193.30		
38	34	197.00	204.50	194.30		
39	35	198.40	205.50	195.80		
40	36	199.20	206.50	197.00		
41	37	200.40	207.50	197.90		
42	38	201.60	208.70	199.20		
43	39	202.60	209.70	200.40		
44	40	203.60	210.90	201.60		
45	41	204.50	211.60	202.60		
46	42	205.80	212.80	203.80		
47	43	207.00	213.60	204.80		

X-708 DATA

	A	B	C	D	E	F
48			2.5 KW			
49	TIME	STK IN	STK OUT	TCE		
50	(MIN.)	(DEG. F)	(DEG. F)	(DEG. F)		
51	44	208.00	214.80	206.00		
52	45	208.70	215.80	206.70		
53	46	209.90	216.70	208.20		
54	47	210.90	217.70	208.90		
55	48	211.90	218.70	210.20		
56	49	212.80	219.70	210.90		
57	50	213.80	220.70	212.40		
58	51	215.00	221.90	213.30		
59	52	215.80	222.60	214.30		
60	53	216.70	223.60	215.00		
61	54	217.70	224.30	216.00		
62	55	218.50	225.50	216.70		
63	56	219.40	226.50	218.20		
64	57	220.40	227.00	218.70		
65	58	221.40	228.20	219.90		
66	59	222.10	229.00	220.40		
67	60	223.10	229.90	221.60		
68	61	223.80	230.70	222.40		
69	62	224.80	231.60	223.30		
70	63	225.50	232.40	224.30		
71	64	226.50	233.30	225.30		
72	65	227.50	234.30	226.30		
73	66	228.20	235.10	226.80		
74	67	229.00	235.80	227.70		
75	68	229.90	236.50	228.50		
76	69	230.70	237.70	229.20		
77	70	231.40	238.40	230.20		
78	71	232.40	239.00	230.70		
79	72	233.10	239.90	231.90		
80	73	233.80	240.40	232.40		
81	74	234.60	241.40	233.30		
82	75	235.30	242.10	234.10		
83	76	236.00	242.60	234.80		
84	77	236.80	243.60	235.50		
85	78	237.70	244.30	236.30		
86	79	238.20	245.10	237.00		
87	80	239.00	245.60	237.70		
88	81	239.70	246.50	238.50		
89	82	240.70	247.50	239.20		
90	83	241.20	248.00	239.90		
91	84	242.60	249.50	241.40		
92	85	243.10	250.00	241.90		
93	86	183.50	216.70	165.20		
94	87	177.90	207.00	155.70		

X-708 DATA

	G	H	I	J	K	L
1			3 KW			
2	TIME	STK IN	STK OUT	TCE		
3	(MIN.)	(DEG. F)	(DEG. F)	(DEG. F)		
4	0	179.60	197.20	146.20		
5	1	177.90	196.50	148.10		
6	2	179.10	196.00	150.10		
7	3	179.40	196.00	149.10		
8	4	179.10	196.20	150.30		
9	5	179.40	196.50	150.80		
10	6	179.40	196.70	151.60		
11	7	179.60	197.00	152.00		
12	8	179.90	197.20	152.80		
13	9	180.10	197.50	153.80		
14	10	180.40	197.90	154.70		
15	11	180.60	197.90	155.70		
16	12	180.90	198.70	157.90		
17	13	180.90	199.40	160.10		
18	14	181.10	200.40	162.10		
19	15	179.60	200.10	164.00		
20	16	179.90	199.70	166.90		
21	17	180.90	199.40	168.40		
22	18	182.10	200.40	170.10		
23	19	184.00	200.90	175.20		
24	20	187.00	201.40	180.60		
25	21	189.20	202.10	185.00		
26	22	191.10	202.80	187.20		
27	23	193.10	203.30	188.90		
28	24	195.00	204.80	191.10		
29	25	196.70	205.50	193.10		
30	26	198.40	207.00	195.00		
31	27	199.90	208.20	197.00		
32	28	201.40	209.70	198.70		
33	29	202.80	210.90	200.10		
34	30	204.30	212.80	201.60		
35	31	205.50	214.10	202.80		
36	32	207.00	215.50	204.50		
37	33	208.20	216.70	205.80		
38	34	209.90	218.20	207.50		
39	35	210.90	219.40	208.70		
40	36	212.60	220.70	210.40		
41	37	213.60	221.90	211.60		
42	38	215.00	223.30	213.30		
43	39	216.30	224.30	214.30		
44	40	217.70	226.00	215.80		
45	41	218.70	227.00	216.70		
46	42	220.20	228.50	218.50		
47	43	221.10	229.40	219.40		

X-708 DATA

	G	H	I	J	K	L
48			3 KW			
49	TIME	STK IN	STK OUT	TCE		
50	(MIN.)	(DEG. F)	(DEG. F)	(DEG. F)		
51	44	222.60	230.90	220.90		
52	45	223.80	232.10	222.10		
53	46	224.80	232.90	222.90		
54	47	226.00	234.10	224.30		
55	48	227.20	235.30	225.50		
56	49	228.50	236.50	226.80		
57	50	229.40	237.50	228.00		
58	51	230.70	239.00	229.00		
59	52	231.90	239.90	230.20		
60	53	232.90	241.20	231.40		
61	54	234.10	241.90	232.40		
62	55	235.10	243.10	233.80		
63	56	236.00	244.10	234.60		
64	57	237.00	245.10	235.50		
65	58	237.50	245.80	236.00		
66	59	238.20	246.00	236.80		
67	60	239.50	247.50	238.00		
68	61	240.20	248.50	239.00		
69	62	241.60	249.50	239.90		
70	63	232.90	247.00	221.10		
71	64	206.50	238.00	190.10		
72						
73						
74						
75						
76						
77						
78						
79						
80						
81						
82						
83						
84						
85						
86						
87						
88						
89						
90						
91						
92						
93						
94						

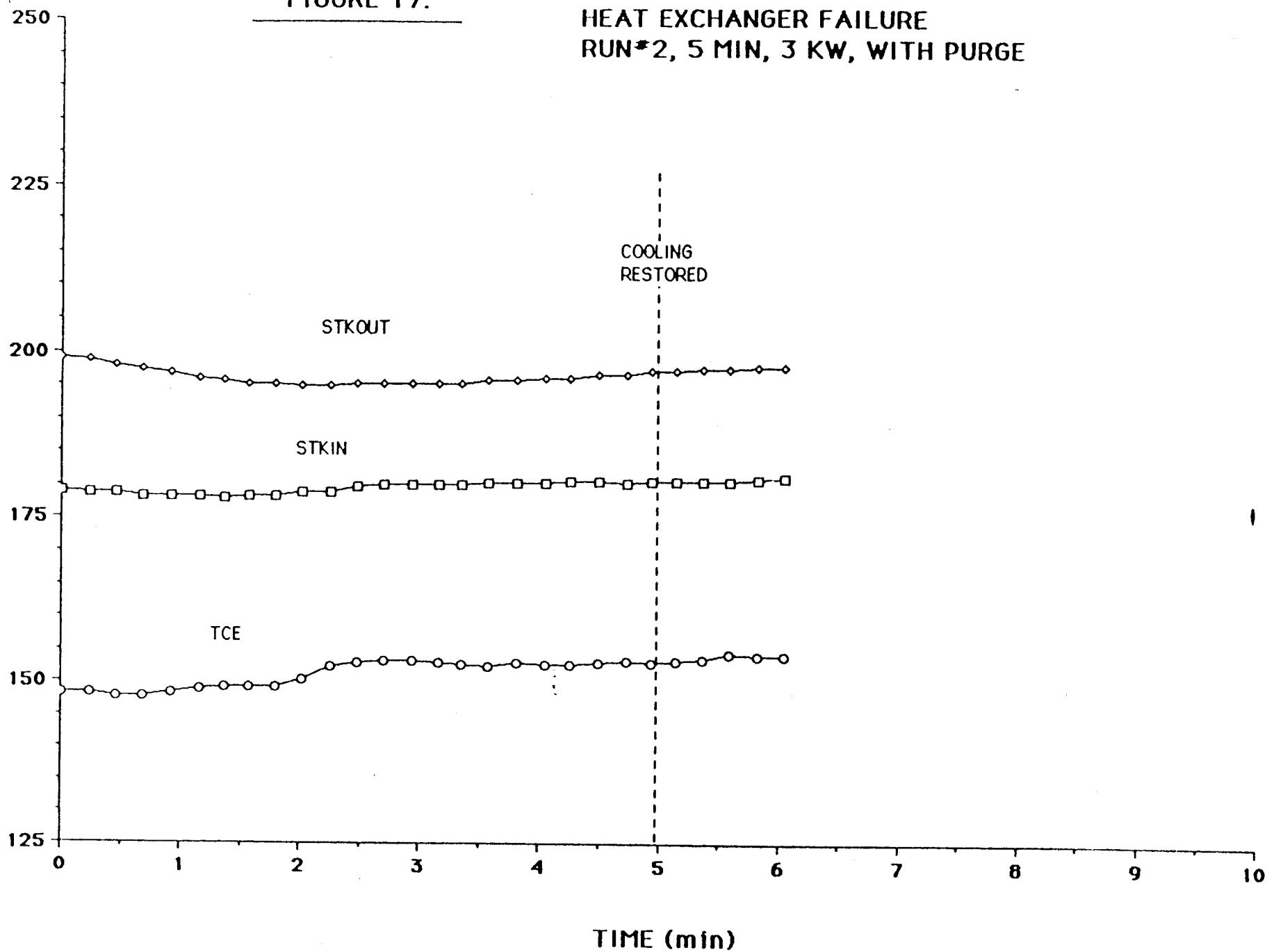
X-708 DATA

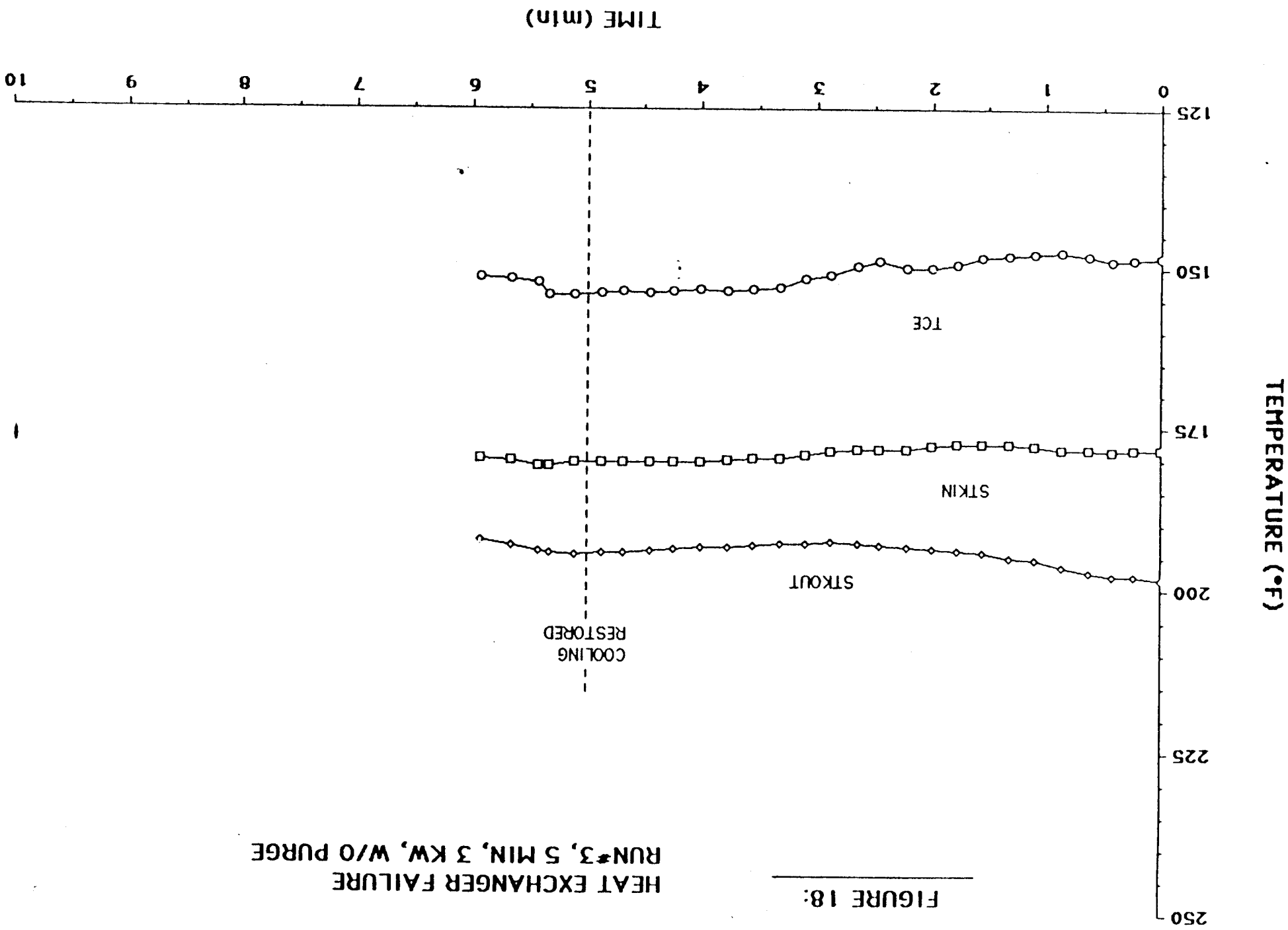
	M	N	O	P
1			4.1 KW	
2	TIME	STK IN	STK OUT	TCE
3	(MIN.)	(DEG. F)	(DEG. F)	(DEG. F)
4	0	178.70	199.40	148.90
5	1	177.70	190.20	148.10
6	2	179.40	197.00	150.30
7	3	178.90	197.20	152.30
8	4	180.10	198.40	156.20
9	5	180.40	199.90	156.70
10	6	180.60	201.60	159.60
11	7	179.90	201.90	161.80
12	8	180.60	201.60	167.20
13	9	180.60	202.10	170.80
14	10	181.10	203.10	174.30
15	11	183.10	203.80	175.70
16	12	189.60	204.80	183.10
17	13	193.10	206.20	188.70
18	14	196.00	208.40	192.10
19	15	198.40	210.40	194.50
20	16	201.10	212.80	197.70
21	17	203.30	214.80	200.10
22	18	206.00	217.50	203.10
23	19	208.20	219.40	205.30
24	20	210.60	222.10	208.00
25	21	212.60	223.80	210.20
26	22	215.00	226.50	212.60
27	23	217.00	228.20	214.50
28	24	219.40	230.40	217.20
29	25	221.40	232.40	218.90
30	26	223.30	234.30	220.90
31	27	225.80	236.80	223.30
32	28	227.50	238.20	225.30
33	29	229.70	240.70	227.50
34	30	231.60	242.40	229.20
35	31	233.80	244.60	231.60
36	32	235.30	246.30	233.30
37	33	237.50	248.50	235.30
38	34	239.20	250.00	237.00
39	35	218.90	245.60	205.00
40	36	199.90	234.30	183.10
41	37	181.60	217.50	162.30
42	38	177.40	203.80	151.10
43				
44				
45				
46				
47				

FIGURE 17:

HEAT EXCHANGER FAILURE
RUN#2, 5 MIN, 3 KW, WITH PURGE

TEMPERATURE (F)





TEMPERATURE (°F)

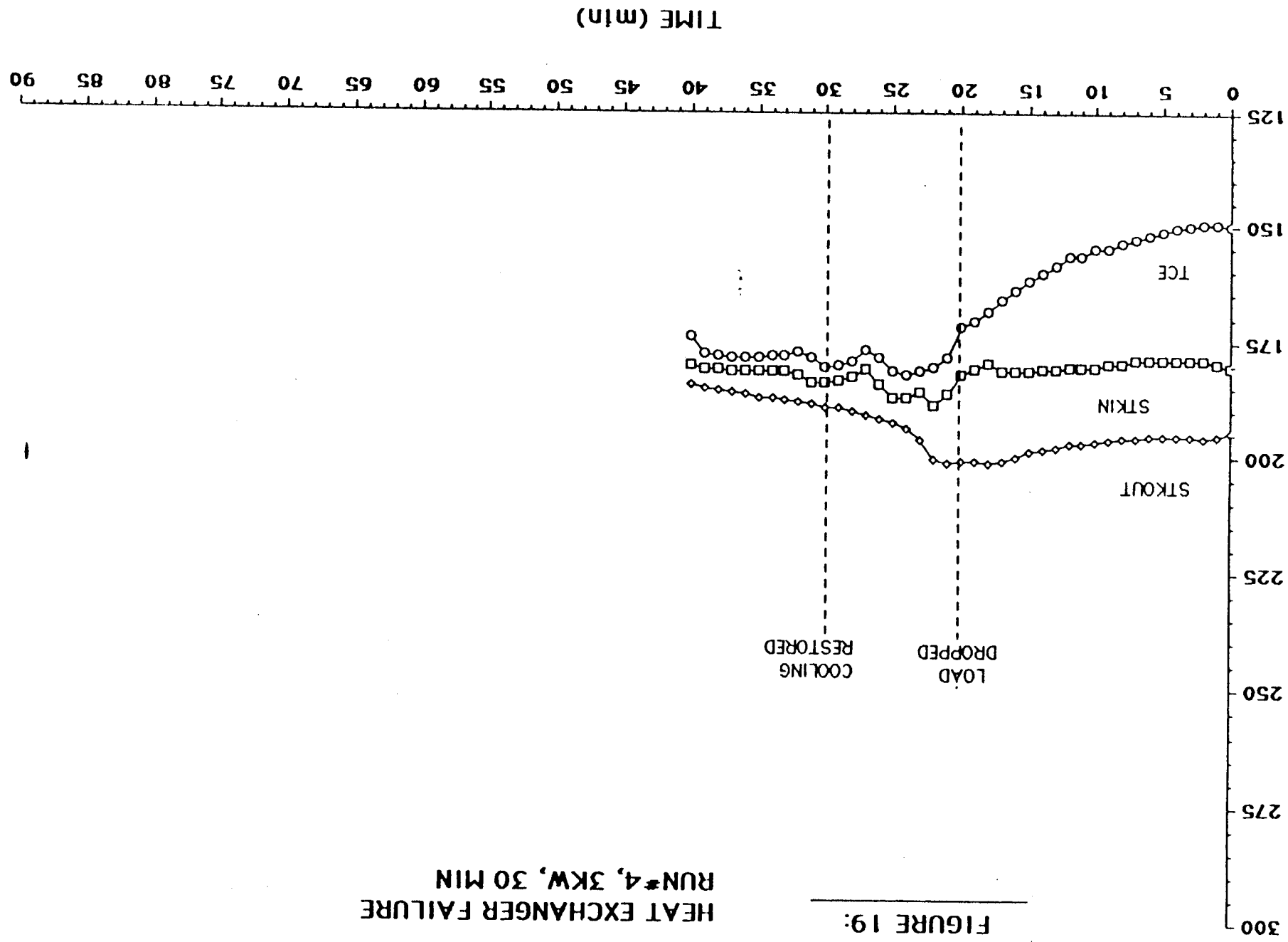


FIGURE 19:

HEAT EXCHANGER FAILURE
RUN#4, 3KW, 30 MIN

TEMPERATURE (°F)

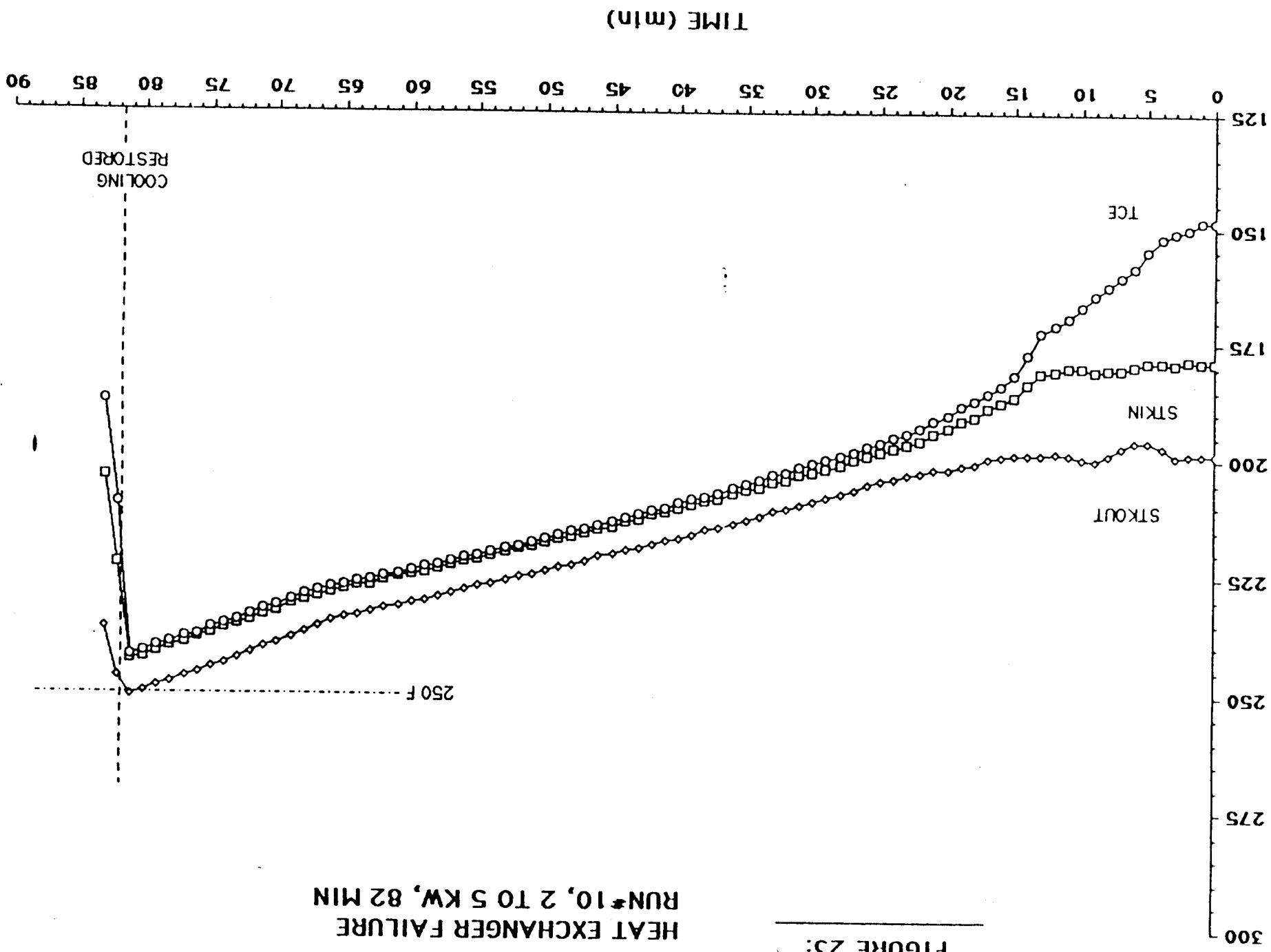
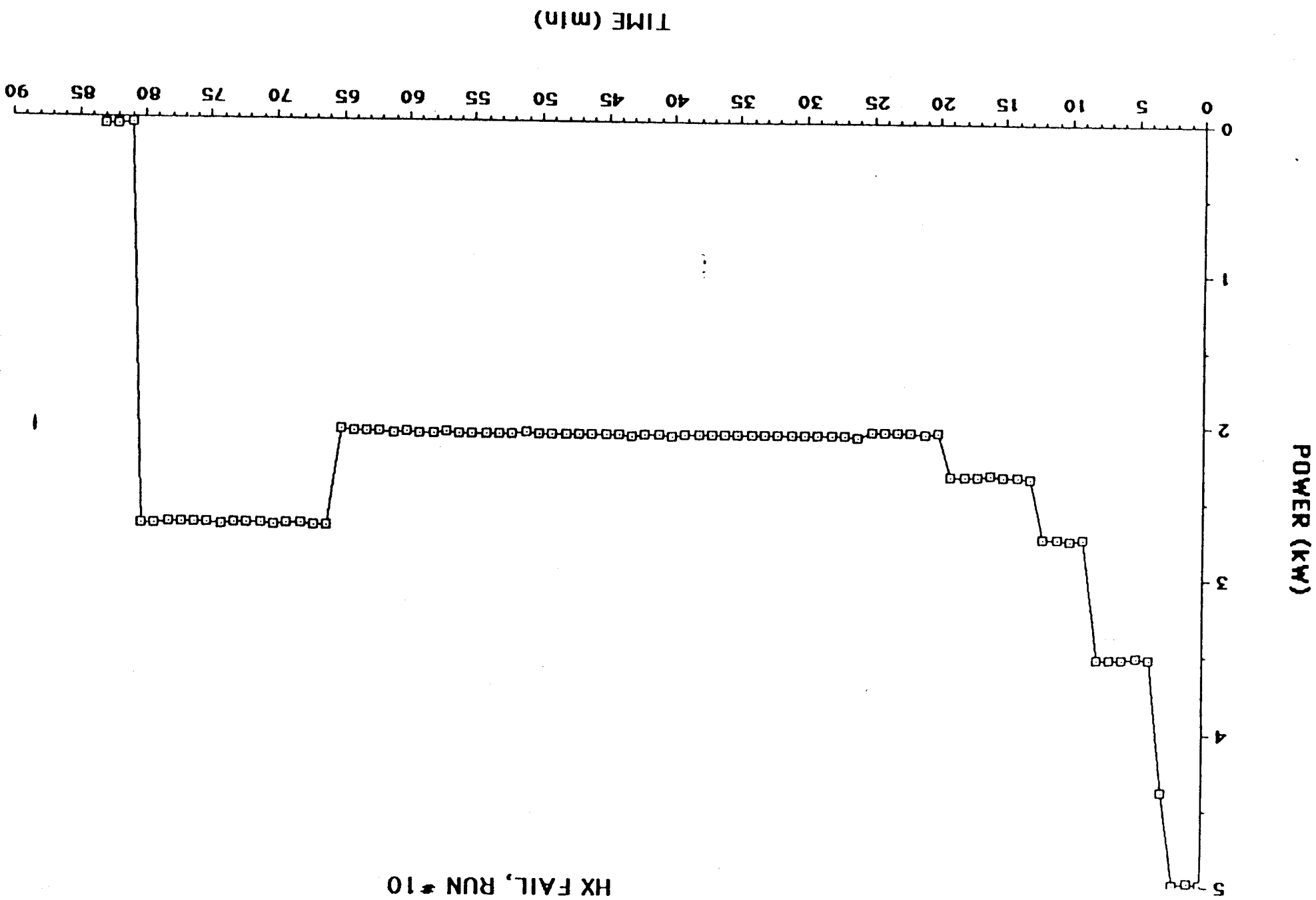


FIGURE 23:

FIGURE 24:
POWER PROFILE
HX FAIL, RUN # 10

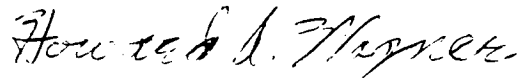


Dr. Jeffery Morehouse
Department of Mechanical Engineering
University of South Carolina
Columbia, S.C. 29208

Dear Jeff,

I could not find any of the X-708 test data or records of the previous work on the fuel cell simulation program. All that information was stored in my old office over the past year. Nobody appears to know what was done to the records when the new people in EP5 moved into that office. I reconstructed the fuel cell stack in, stack out, and condenser outlet temperatures from some plots stored in the computer. I also included the default input parameters for the simulation program. I know that some of the flow rates and heat exchanger temperature values will be off. During the X-708 test program the fuel cell was purged during the tests for failure of the fuel cell heat exchanger. You will just have to guess what those flow rates were. If you have any questions call me at (713) 483-9048.

Sincerely,

A handwritten signature in cursive script, appearing to read "Howard A. Wagner".

Howard A. Wagner

APPENDIX B:
FCPSIM COMPUTER CODE LISTING

```

C *** PROGRAM FCPSIM (FUEL CELL SIMULATION)
C
C *** INPUTS
C
C     LOGICAL OLD
C     CHARACTER VAC=5,STACK=10
C
C *** INITIALIZE
C
C     IEC=1999.16
C     W2=0
C     W02=1.133
C     T02IN=-300.0
C     W=0.166
C     T02IN=-300.0
C     T02=-300.0
C     W=0.166
C     T02=90.0
C     WRITE(6,3)
C
C     FORMAT(5X,'SELECT OPTION TO UPDATE//5X,'1: FC POWER (1999.16)
C     & 2: FC TYPE (1='OLD')//5X,'3: O2 SUPPLY FLOW RATE (1.133)
C     & 4: O2 SUPPLY TEMPERATURE (-300)//5X,'5: H2 SUPPLY FLOW
C     & 6: H2 SUPPLY TEMPERATURE (-300)//5X,'7:
C     & 8: ENVIRONMENTAL TEMPERATURE (50.0)//5X,'9: ENVIRONMENTAL
C     & 10: CONDITION (0='VACUUM')//5X,'11: EXTERNAL HEAT EXCHANGER
C     & 12: TEMPERATURE (90.0)//5X,'HIT RETURN WHEN FINISHED TO
C     & 13: EXECUTE PROGRAM//)
C
C     READ(5,25)NFLAG
C     IF(NFLAG.EQ.1)THEN
C         WRITE(6,10)
C     10     FORMAT(1X,'ENTER FUEL CELL POWER IN WATTS')
C         READ(5,15)PFC
C     15     FORMAT(F8.3)
C         GOTO 1
C     END IF
C     IF(NFLAG.EQ.2)THEN
C         WRITE(6,20)
C     20     FORMAT(1X,'ENTER FUEL CELL TYPE//5X,'1: 2 SUBSTACK',10X,
C     & 2: 3 SUBSTACK')
C         READ(5,25)NEW
C     25     FORMAT(I1)
C         GOTO 1
C     END IF
C     IF(NEW.EQ.1)OLD=.TRUE.
C     IF(NEW.EQ.2)OLD=.FALSE.
C     IF(NFLAG.EQ.3)THEN
C         WRITE(6,30)
C     30     FORMAT(1X,'ENTER O2 SUPPLY (REACTANT PLUS PURGE) FLOW RATE IN
C     & 4: LB/HR')
C         READ(5,15)W02
C         GOTO 1
C     END IF
C     IF(NFLAG.EQ.4)THEN
C         WRITE(6,35)
C     35     FORMAT(1X,'ENTER O2 SUPPLY TEMPERATURE IN DEG F')
C         READ(5,15)T02IN
C         GOTO 1
C     END IF
C     IF(NFLAG.EQ.5)THEN

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

        WRITE(6,40)
40      FORMAT(1X,'ENTER H2 SUPPLY (REACTANT PLUS PURGE) RATE IN LB/HR')
        READ(5,15)WH2
        GOTO 1
    END IF
    IF(NELAG.EQ.6)THEN
        WRITE(6,45)
        FORMAT(1X,'ENTER H2 SUPPLY TEMPERATURE IN DEG F')
        READ(5,15)TEH2
        GOTO 1
    END IF
    IF(NELAG.EQ.7)THEN
        WRITE(6,50)
        FORMAT(1X,'ENTER ENVIRONMENTAL TEMPERATURE IN DEG F')
        READ(5,15)TEHX
        GOTO 1
    END IF
    IF(NELAG.EQ.8)THEN
        WRITE(6,55)
        FORMAT(1X,'ENTER ENVIRONMENTAL CONDITION/EX: 1: VACUUM, 2: AIR')
        READ(5,15)E
        GOTO 1
    END IF
    IF(NELAG.EQ.9)THEN
        WRITE(6,60)
        FORMAT(1X,'ENTER EXTERNAL HEAT EXCHANGER TEMPERATURE IN DEG F')
        READ(5,15)TEHX
        GOTO 1
    END IF
    WRITE(6,65)
    65  FORMAT(1X,'ENTER CALCULATION TIME STEP SIZE IN SECONDS')
        READ(5,15)DTIME
        DTIME=DTIME/3600.0
        WRITE(6,70)
    70  FORMAT(1X,'ENTER PRINTOUT TIME STEP SIZE IN SECONDS')
        READ(5,15)PTIME
        PTIME=PTIME/3600.0
C
C *** OUTPUT HEADINGS
C
        OPEN(UNIT=8,FILE='FCPSIM.OUT',STATUS='UNKNOWN')
        IF(OLD.EQ..TRUE.)THEN
            STACK='2 SUBSTACK'
        ELSE
            STACK='3 SUBSTACK'
        END IF
        IF(Z.LE.0.5)THEN
            VAC='VACUUM'
        ELSE
            VAC='AIR'
        END IF
        WRITE(8,90)PEC,STACK,VAC,W02,T02IN,WH2,TH2IN,TEHV,TEHX
    90  FORMAT(1X,'FUEL CELL WATTS:',F7.1,3X,A10,3X,A6/1X,'O2 SUPPLY'
        & ' FLOW RATE(LB/HR): ',F5.2,3X,'O2 SUPPLY TEMPERATURE (DEG F): ',
        & ' F6.1/1X,'H2 SUPPLY FLOW RATE (LB/HR): ',F5.3,3X,'H2 SUPPLY'
        & ' TEMPERATURE (DEG F): ',F6.1/1X,'ENVIRONMENTAL TEMPERATURE'
        & ' (DEG F): ',F6.1/1X,'EXTERNAL HEAT EXCHANGER TEMPER'
        & ' ATURE (DEG F): ',F5.1//)
        WRITE(8,100)

```

ORIGINAL PAGE IS
OF POOR QUALITY


```

100  FORMAT(2X,'TIME   TSKO   TFC   QGEN   QCFC   QFCEN',
&    ' QFCRE   CURR   VFC   TCFHO'/2X,'TQ2OUT   QPHO2   QPHOEN',
&    ' TH2OUT TCFHH   QPHH2   QPHHEN   TCF   QCPEN   WC'/2X,
&    ' WCB1   WCB2   WCEH1   WCC   T2HX   QHXEN   QEHX',
&    ' TCE   QEVEN   WCC'/2X,'TCCO   QCOND   QODEN   ',
&    ' THI   WH2T   TMEX   TCCI   TSKIN   QSSHEH'//)
C
C *** PHYSICAL PARAMETERS *****
C
C *** OXYGEN SPECIFIC HEAT
C
C      QPO2=0.05
C      QPO2=0.007
C
C *** HYDROGEN SPECIFIC HEAT
C
C      QPH2H=3.15
C      QPH2=2.8
C
C *** WATER SPECIFIC HEAT AND LATENT HEAT
C
C      QPH2O=0.451
C      HEATL=1006.4
C
C *** THERMAL PROPERTIES
C
C      SIG=0.1714E-8
C      EMIS=0.85
C      HCONV=1.0
C
C *** THERMAL MASS OF COMPONENTS
C
C *** FUEL CELL
C
C      IF(OLD.EQ..TRUE.)CMFC=36.5*0.7
C      IF(OLD.EQ..FALSE.)CMFC=39.75*0.7
C
C *** OXYGEN PREHEATER
C
C      CMPHO=0.16
C      APHO=0.28
C      EPHO2=0.9
C
C *** HYDROGEN PREHEATER
C
C      CMPHH=0.10
C      APHH=0.146
C      EPHH2=0.9
C
C *** COOLANT PUMP
C
C      WKCP=410.0
C      CMCP=0.42
C      ACP=0.795
C
C *** EXTERNAL HEAT EXCHANGER
C
C      IF(OLD.EQ..TRUE.)THEN
C          CMHX=7.09*0.5
C          AEHX=6.03*0.3

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

ELSE
  CMEHX=2.19
  AEHX=0.904
END IF
C
C *** THERMAL CONTROL VALVE
C
  CMECV=1.50
  ACECV=0.9
C
C *** CONDENSER
C
  TPCND=3.07
  TPCND=0.61
C
C *** START/SUSTAINING HEATERS
C
  TMSSH=1.44
  ASSH=0.69
C
C *** INITIAL VALUES *****
C
C *** FUEL CELL
C
  TSTOP=110.0/60.0
  TSTART=20.0/60.0
  TSKIN=180.7
  TEC=0.0047*PFC+178.6
  TSKO=TEC-2.0
  WC=0.25.0
  VFC=30.0
  WQZF=0.67*PFC/1000.0
  WHZF=0.085*PFC/1000.0
  WHZ1=WHZ
  WQZ1=WQZ
C
C *** O2 PREHEATER
C
  TCPHO=TSKO-2.0
  QPHO2=100.0
C
C *** H2 PREHEATER
C
  TSPHH=TCPHO-2.0
C
C *** COOLANT PUMP
C
  TCP=TCPHO+1.0
C
C *** CONDENSER CONTROL VALVE
C
  TCE=151.7
  TCEPP=TCE
  TCEP=TCE
  WCB2=0.02*PFC
C
C *** CONDENSER
C
  TBP=0.003*PFC+154.0
  TCCO=177.7

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

      TCCOP=TCCO
      TCCI=113.0
      TCCIP=TCCI
      WH2OR=6.15
      WH2REC=10.2
C
C *** STACK INLET CONTROL VALVE
C
      TWIX=18.0+0.0005*PV
      TWIXP=TWIX
C
C *** START/SLUICING1 -ENTER
C
      TSSB=TWIX-1.0
      TSS=0.0
C
C
C *** BEGINNING OF SYSTEM COMPONENT EQUATIONS *****
C *** FUEL CELL STACK
C
C *** PARAMETERS
C
      CURR::FUEL CELL CURRENT (AMPS)
      PEC::FUEL CELL POWER (WATTS)
      VEC::FUEL CELL VOLTAGE(VDC)
      ECKW::FUEL CELL HEAT GENERATION (BTU/HR)
      ECEFF::FUEL CELL EFFICIENCY
      QGEN::FUEL CELL HEAT GENERATION (BTU/HR)
      WH2F::FUEL CELL HYDROGEN CONSUMPTION (LB/HR)
      WO2F::FUEL CELL OXYGEN CONSUMPTION (LB/HR)
      WH2OF::FUEL CELL WATER PRODUCTION RATE (LB/HR)
      TSKO::FUEL CELL STACK EXIT TEMPERATURE (DEG F)
C
C *** COOLANT SPECIFIC HEAT
C
      200   CPC=0.23124+0.0002111*TSKIN
C
C *** KEEPING REACTANT FLOW BEFORE ACCIDENT START
C
      IF(TIME.LT.TSTART)THEN
        WO2=WO2F
        WH2=WH2F
      ELSE
        WO2=WO2I
        WH2=WH2I
      END IF
C
C *** POWER/CURRENT/VOLTAGE RELATIONS
C
      CURR=PEC/VEC
      IF(OLD.EQ..TRUE.)THEN
        IF(CURR.LE.131)THEN
          SLOPE=-0.0171
          YINT=32.67
        ELSE
          SLOPE=-0.01099
          YINT=31.87
        END IF
      END IF

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

ELSE
  IF(CURR.LE.180)THEN
    SLOPE=-0.0104
    YINT=32.775
  END IF
  IF((CURR.GT.180).AND.(CURR.LT.25))THEN
    SLOPE=-0.0085
    YINT=32.143
  END IF
  IF(CURR.LE.25)THEN
    SLOPE=-0.0075
    YINT=31.544
  END IF
  SLOPE=
  YINT=
  EPOCH=
  EPOCH=TECP-180.0
  BQ=-(YINT+0.003*STEP)
  ECHW=3.413*PEC
  QRE=PEC*(SLOPE+0.33E-5*STEP)
  QDQ=-(BQ+SQRT(BQ**2-4.0*Q3))/2.0
  ECEFF=QDQ/39.26
  QGEN=ECHW*(1.0-EC EFF)/ECEFF
  CURR=PEC/QDQ
  W02F=CURR*2.106E-2
  WH2F=CURR*2.653E-2
  WH2OF=CURR*2.371E-2
  T02OUT=T02IN+QF02/(W02*CP02H)
  WH2O=WH2OF+WH2OF
  WH2T=WH2F+WH2REC
  THHP=TCE+2.0
  TECP=TEC
  QFCRE=-(WH2OR*CPH2O+WH2T*CPH2)*THHP-W02*CP02*T02OUT+(WH2O*CPH2O
& +WH2REC*CPH2)*TECP+(W02-W02F)*CP02*TECP
  QECEN=1.163E-10*((TSKO+460.0)**4-(TENV+460.0)**4)+ZA0.00136*10**
& (0.249*ALOG10(2.16E6*(TSKO-TENV))-0.27)*(TSKO-TENV)
C   TECP=(QGEN-QFCRE-QECEN+WC*CPA*(2+TSKIN))/(WC*CPC)
C   TECP=(TECP+TEC)/2.0
C   TEC=(QGEN-QFCRE-QECEN+WC*CPA*(2.0+TSKIN)+CMFC*TECP/DTIME)
C   & /(WC*CPC+CMFC/DTIME)
  DELTEC=(QGEN-QFCRE-QECEN+WC*CPA*(TSKIN-TSKO))*(DTIME/CMFC)
  TEC=TECP+DELTEC
  TDROP=(4.0+WC/1100.0)+(4.0*PEC/12000.0)
  TSKO=TEC-TDROP
  QCFC=WC*CPA*(TSKO-TSKIN)
C
C *** O2 PREHEATER
C
C *** PARAMETERS
C
C   CMPHO  (MC) OF O2 PREHEATER
C   APHO   SURFACE AREA (0.28 SQ FT)
C   W02    FLOW RATE OF O2 (LB/HR)
C   TENV   ENVIRONMENTAL TEMPERATURE (DEG R)
C   EMIS   EMISSIVITY OF PREHEATER SURFACE (0.85)
C   HCONV  CONVECTION COEFFICIENT IN AIR (BTU/HR SQ FT DEG R)
C   Z      FLAG(1.0 FOR AIR ENVIRONMENT, 0 FOR VACUUM ENVIRONMENT)
C   T02IN  O2 SUPPLY TEMPERATURE (DEG R)
C   EPHO2  EFFECTIVENESS OF O2 PREHEATER (0.90)
C   SIG    STEPHAN-BOLTZMAN CONSTANT (0.1714E-8 BTU/HR SQ FT DEG R**4)
C   CP02H  SPECIFIC HEAT OF O2 SUPPLY

```

ORIGINAL PAGE
OF POOR QUALITY


```

      B1=800.0
      B2=1400.0
      END IF
      IF(TCP.LE.A1)WC=B1
      IF(TCP.GE.A2)WC=B2
      IF((TCP.GT.A1).AND.(TCP.LT.A2))WC=B1+(B2-B1)*(TCP-A1)/(A2-A1)

C *** MIXING VALVE CONTROL VALVE
C
C *** PARAMETERS
C
C      TMIXP  PREVIOUS MIXING TEMPERATURE (DEG F)
C      WCB1   COOLANT FLOW RATE IN MIXING VALVE (LBS/HR)
C      WCC     TOTAL COOLANT FLOW RATE (LBS/HR)
C      WCD     FLOW RATE IN CONDENSER (LBS/HR)

      TMIX=ABS(TMIA-TMIXP)
      IF(TMIX.LE.0.1)GOTO 10
      TMIXP=TMIXP+(TMIX-TMIXP)*0.01/(TMIX+0.01)
10    ELSE
      TMIXP=TMIX
      END IF
      IF(TMIXP.GE.185.0)WCB1=0.0
      IF(TMIXP.LE.181.0)WCB1=WC-140.0
      IF((TMIXP.GT.181.0).AND.(TMIXP.LT.185.0))WCB1=(WC-140.0)*(185.0
& -TMIXP)/4.0
      WCC=WC-WCB1
      IF(QCOND.GT.QCOND0)WCC=(QCOND+WCC)/QCOND0
      IF(WCC.LT.0.0)WCC=WC
      IF(WCC.GE.WC)WCC=WC
      WCB1=WC-WCC
C *** ENERGY BALANCE ON MIXING VALVE GIVES TCCO
C
      TCCO=(WC*TMIXP-WCB1*TCP)/WCC
C
C
C
C *** CONDENSER (BACKWARDS THROUGH IT!)
C
      WH2O=WH2OF+WH2OR
      WH2T=WH2+WH2REC
      THI=(WH2*CPH2*TH2OUT+WH2REC*CPH2*TEC+WH2O*CPH2O*TEC)/(WH2T
& *CPH2+WH2O*CPH2O)
      QSENH=(WH2T*CPH2+WH2O*CPH2O)*(THI-TDP)
      QLAT=HEATLAWH2OF
      QSENL=(WH2T*CPH2+WH2OR*CPH2O)*(TDF-TCE)
      IF((TIME.GT.TSTART).AND.(TCE.GT.TDP))THEN
        QSENL=0.0
        QLAT=0.0
      END IF
      QCOND=QSENH+QLAT+QSENL
      TCCIP=TCCI
      QCDEN=SIG*EMIS*ACOND*((THI+460.0)**4-(TENV+460.0)**4)+Z*HCONVA
& *ACOND*(THI-TENV)
      TCCI=(WCC*CPH2*TCCO+QCDEN-QCOND)/(WCC*CPH2)
C      TCCI=(WCC*CPH2*TCCO+QCDEN-QCOND+QCOND0*(TCCO-TCCOF-TCCI)/
C      & (2.0*DTIME))/(WCC*CPH2+QCOND/(2.0*DTIME))
      IF(TCCI.LE.THX)TCCI=TEHX
C

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

C      GENHX  HEAT TRANSFER TO THE EXTERNAL HEAT EXCHANGER
C
      TEHXP=TEHX
      QHXEN=SIG*EMIG*ASHX*((TEHXP+460.0)**4-(TENV+460.0)**4)+ZAHCON/A
      & AEHX*(TEHXP-TENV)
      IF (TIME.GE.TSTART) THEN
        TEHX=(1-QHXEN-ATEHX*CPH1-TEP*CHEN1+TEHXP/DTIME)
        & ((QHX+QCI)-TEHX*CHEN1)
        IF
          GENHX=4*TEHX*TEP*(TEHX-TEP)
C
C *** CONDENSER (OVERLOADS THROUGH TCCO)
C
C *** PARAMETERS
C
C      WH2    FLOW RATE OF HYDROGEN (LB/HR)
C      WH2PEC RECIRCULATION FLOW RATE OF HYDROGEN (LB/HR)
C      W2IF    HYDROGEN CONSUMPTION RATE (LB/HR)
C      WH2T    TOTAL HYDROGEN FLOW RATE (LB/HR)
C      THI     H2 TEMPERATURE INTO THE CONDENSER (DEG F)
C      WH2OR    WATER RECIRCULATION RATE IN HYDROGEN PUMP (LB/HR)
C      CPH2     SPECIFIC HEAT OF HYDROGEN
C      TH2OUT   TEMPERATURE OF H2 EXITING THE H2 PREHEATER (DEG F)
C      TFC      TEMPERATURE OF THE FUEL CELL (DEG F)
C      WH2O     FLOW RATE OF WATER EXITING THE FUEL CELL (LB/HR)
C      CPH2O    SPECIFIC HEAT OF WATER
C      QCOND    HEAT TRANSFER IN THE CONDENSER (BTU/HR)
C      TCE      TEMPERATURE AT CONDENSER EXIT (DEG F)
C      HEATL    LATENT HEAT OF CONDENSATION
C      QCDEN    ENVIRONMENTAL HEAT LOSS (BTU/HR)
C      TCCO     TEMPERATURE OF COOLANT EXITING THE CONDENSER (DEG F)
C      WCC      COOLANT FLOW RATE THROUGH CONDENSER (LB/HR)
C      CMCOND   (MC) OF THE CONDENSER
C      TCCOP    PREVIOUS TEMPERATURE COOLANT EXITING CONDENSER (DEG F)
C      TCEP     PREVIOUS CONDENSER EXIT H2 TEMPERATURE
C      DTIME    TIME STEP
C
      TCCOP=TCCO
C      QCOND=WH2T*CPH2*(THI-TCE)+WH2OF*HEATL+WH2O*CPH2O*(THI-TCE)
      TCCO=(-QCDEN+QCOND+WCC*CPC*TCCI)/(WCC*CPC)
C      TCCO=(-QCDEN+QCOND+WCC*CPC*TCCI+CMCOND*(TCCO+TCCOP
      & -TCCI)/(2.0*DTIME))/(WCC*CPC+CMCOND/(2.0*DTIME))
C *** TO GET TCCO (AND THUS TCCI ALSO) TO 'SEEK' LOW OPERATING TEMPS
      TCCOM=TEHX+QCOND/(WCC*CPC)
      IF ((TCCO.GT.TCCOM).AND.(TCE.GT.153.0)) TCCO=(TCCOM+TCCO)/2
C *** TO PREVENT TCCO EXITING HOTTER THAN SOURCE
      IF (TCCO.GE.THI-2.0) TCCO=THI-2.0
C *** TO BALANCE HEAT FLOW FROM H2 TO COOLANT (SEE STACK INLET VALVE ABOVE)
      QCOND=C=WCC*CPC*(TCCO-TCCI)
C
C
C *** STACK INLET CONTROL VALVE
C
C *** PARAMETERS
C
C      TMIX    MIXING VALVE TEMPERATURE (DEG F)
C      WCC      COOLANT FLOW RATE EXITING CONDENSER (LB/HR)
C      CPC      SPECIFIC HEAT OF COOLANT
C      TCCO     COOLANT TEMPERATURE EXITING CONDENSER (DEG F)

```


IF(TIME.LE.TSTOP)GOTO 200
CLOSE(UNIT=8)
STOP
END

ORIGINAL PAGE IS
OF POOR QUALITY